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The Consumption Footprint as possible indicator for environmental impact evaluation at city level. The case study of Turin (Italy)

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ABSTRACT

Environmental assessment methods have increasingly been adopted to support local transitions toward sustainable urban development and Agenda 2030 implementation at the city level. However, available methods evaluating both direct and indirect (embodied) environmental impacts due to local consumption are still limited and lack a broad coverage of environmental issues. Adopting a Life Cycle Assessment (LCA) perspective in current approaches may help to fill this gap. In this paper, we evaluated the environmental impacts associated to consumption patterns and intensities of the average Turin citizen (Italy) by implementing the LCA-based Consumption Footprint indicator, which assesses the impacts of five areas of consumption (food, mobility, housing, household goods, appliances) with the 16 impact categories of the Environmental Footprint method. Comparing Turin and EU consumption patterns, the average Turin citizen showed a larger impact on human toxicity (+30%) and a lower on ozone depletion (-21%) with housing, food, and mobility as main drivers. This represents a first attempt in assessing local consumption with full bottom-up LCA indicators. The Consumption Footprint allowed unveiling local consumption trends while connecting them to a global dimension of impacts (e.g., Planetary Boundaries). Main challenges include input data types (e.g., local consumption intensities) and coverage of consumer goods modelled via the proposed indicators.

1. Introduction

During the last decades, human well-being has improved although occurring at the expense of large resource consumption and associated environmental impacts (IRP, 2019). Environmental policy-making focusing on sustainable consumption and production has evolved to address environmental pressures (e.g., emissions of greenhouse gases (GHG)) as well as environmental impacts, such as on biodiversity and ecosystems services (IPBES, 2019). At the international level, the UN Sustainable Development Goals (SDGs) (UN, 2015) include SDG12 on fostering responsible consumption and production patterns, including indicators and targets on natural resources use, food waste, chemicals management and waste generation. Additionally, SDG11 and SDG8 are strictly related to reducing the pressure of human settlements (e.g., targets for the reduction of waste production and pollution in cities) and economies (e.g., decoupling resource use and associated impacts from economic growth) on the environments, respectively.

At the European Union (EU) level, the European Green Deal (EGD) seeks for a modern, resource-efficient and competitive EU economy (EC, 2019). EGD highlights the relevance of value chains and trade, where embedded environmental and social impacts may generate spill-over effects in other world regions due to EU consumption. Such focus on supply chains and consumption, and the opportunity of addressing this via life cycle thinking, has been evolving in EU policies for over 30 years (Sala, Amadei, Beylot & Ardente, 2021).This is stressed in policy documents under the EGD, such as the Farm to Fork Strategy (EC, 2020a), the Biodiversity Strategy (EC2020b), the Circular Economy Action Plan (EC 2020c), the Chemicals Strategy for Sustainability (EC 2020d), and the Zero Pollution Action Plan (EC 2021). A consumption footprint perspective that holistically considers the impacts along the entire value chains is outlined in these documents.

Cities are a crucial hotspot towards sustainability, and are

Abbreviation: BoP, Basket of Product; CE, Circular Economy; EF, Environmental Footprint; EGD, European Green Deal; GHG, Greenhouse Gases; GIS, Geographic Information System; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; MFA, Material Flow Analysis; PEF, Product Environmental Footprint; PG, Product Group; RP, Representative product; SDG, Sustainable Development Goals; UM, Urban Metabolism.

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specifically addressed by the SDG11, due to their dual role. While being main responsible for GHG and other pollutants emissions, resource consumption and waste generation (UN-Habitat 2009), urban areas are hubs for innovation and experimentation of sustainable development solutions. Generally, even if SDGs are set at the global level, at least 100 of 169 targets cannot be fully achieved without the engagement of local and regional governments (Ferruzza, Tagliacozzo & Lombardi, 2021; OECD 2020). Thus, quantifying and monitoring the sustainability of cities is crucial. Consequently, assessment frameworks should consider local specificities, needs and capacities while adopting shared methods allowing comparability with other contexts (Brandon, Lombardi & Shen, 2016).

1.1. The consumption footprint of cities: from urban metabolism to life cycle assessment

The definition of targets and indicators at local scale is recognized as crucial for the achievement of SDGs, hence, the involvement of cities and territories and the creation of dedicated assessment frameworks for urban sustainability evaluation is key. Such aspect has been addressed in international declarations and agreements son sustainable development and climate, such as those presented in (Fig. 1).

In 1992, Local Agenda 21 addressed the development of local plans, actions and initiatives focusing mainly on environmental sustainability and legitimising them at the international level (Voisey, Beuermann, Sverdrup & O'Riordan, 1996). The Covenant of Mayor was a successive European initiative aiming at coordinating voluntary commitments of cities to meet European and international objectives regarding energy and climate. Today more than 10 000 signing cities are committed to reduce their GHG emissions by 30% by 2030 (Bertoldi et al., 2020). However, the approaches adopted for the evaluation of the environmental impacts of cities mainly had a territorial and production perspective by including only direct emissions and partially indirect ones related to energy production (Kona, Bertoldi & Kilkiş, 2019). Nevertheless, including indirect emissions when assessing the environmental impacts of cities is in the spotlight, especially in developed countries where higher consumption lifestyles depend on regional and global hinterlands (Wiedmann & Allen, 2021). The EC recently proposed a set of indicators for Local Voluntary Review (Siragusa, Vizcaino, Proietti & Lavalle, 2020) to support cities in the achievement of SDGs. This document emphasizes the need to use indicators able to evaluate environmental impacts related to consumption and production patterns for SDG12.

A range of methodsable to quantify the environmental impacts of production and consumption patterns in cities are available and can be classified into two main categories: urban metabolism (UM) approaches and footprint-base approaches e.g., ecological footprint, water footprint, carbon footprint). UM aims to model a city based on exchange flows with the environment (i.e., resources use and emissions to the environment) (Beloin-saint-pierre et al. 2017). Although UM enables evaluating local patterns and their transformation along time, the assessment is performed at the pressure level rather than at the impact one. Most footprint approaches are based on a consumption-based perspective considering the entire supply chain (Genta, Favaro, Sonetti, Fracastoro & Lombardi, 2021; Vanham et al., 2019), although these are also still limited to a pressure level (i.e., the flows of resources use or emissions to the environment are not characterised to express their potential environmental impact). In this regard, the inclusion of Life Cycle Assessment (LCA) in the assessment of cities allows to measure environmental impacts (Fig. 2). LCA enables adopting a cradle to grave perspective including consumption-related impacts that occur beyond administrative borders of a globalized city (Goldstein, Birkved, Quitzau & Hauschild, 2013; González-García, Caamaño, Moreira & Feijoo, 2021; Hult & Larsson, 2016), assessing consumption-related impacts against environmental global thresholds (e.g., planetary boundaries) (Wiedmann & Allen, 2021), and supporting decision-making processes in multi-criteria assessments through the identification of hotspots of impacts and priority areas of intervention (Beloin-saint-pierre & Rugani, 2017; Chester, Pincetl & Allenby, 2012). Mirabella, Allacker and Sala (2019) reviewed the use of LCA methodologies for evaluating the environmental impact of cities, highlighting that most studies are a partial attempt and focused on specific urban sectors (e.g., energy sector). Martire, Mirabella and Sala (2018) conducted a preliminary attempt with a more comprehensive assessment

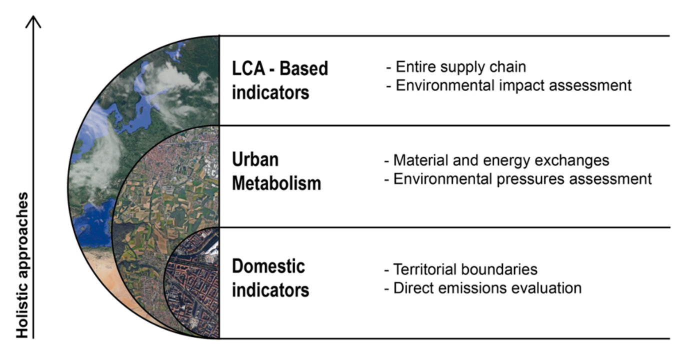

Fig. 2. Evolution of approaches for the evaluation of environmental impacts of cities.

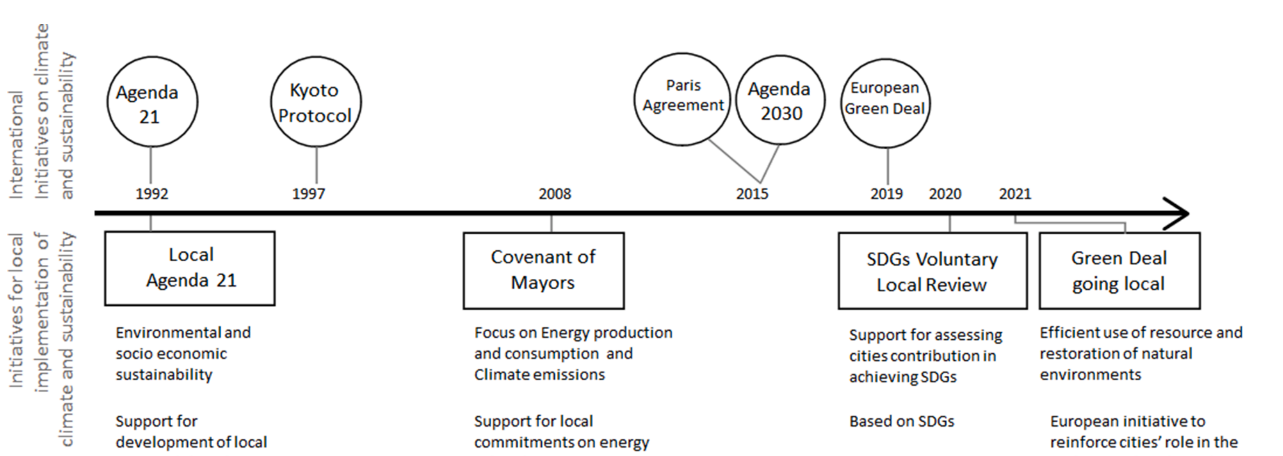

Fig. 1. Main international conventions on climate and sustainable development from 1992 and European local initiatives which implements global commitments involving local authorities (i.e. municipalities).

showing that, e.g., food consumption is a relevant area when considered in the carbon footprint of a city.

To assess the environmental impacts of EU consumption, the European Commission - Joint Research Centre (EC-JRC) developed the Consumption Footprint indicator (Sala & Castellani, 2019; Sala et al., 2019a; EC-JRC, 2022), which aims at comprehensively assessing EU consumption with a process-based LCA approach considering the entire supply chain of around 150 representative products (RPs). RPs in terms of consumption and environmental impacts are selected for five areas of consumption, i.e. housing (Baldassarri, Allacker, Reale, Castellani & Sala, 2017; Lavagna et al., 2018), mobility (Castellani, Fantoni, Cristòbal, Zampori & Sala, 2017a), food (Castellani, Fusi and Sala, 2017; Notarnicola, Tassielli, Renzulli, Castellani & Sala, 2017), household appliances (Hischier, Reale, Castellani & Sala, 2020; Reale, Castellani, Hischier, Corrado & Sala, 2019) and household goods (Castellani et al., 2019; Castellani, Sanyé-Mengual & Sala, 2021). For each RP, consumption intensity is calculated based on consumption statistics and the environmental impact is assessed based on a modelled life cycle inventory (LCI). Compared to urban metabolism with a flow-based approach (e.g., glass, plastic, building materials) (Kennedy, Pincetl & Bunje, 2011), this process-based LCA indicator has a product perspective, where the different material flows are embedded in the life cycle of the products (e.g., plastic bottle as packaging, building materials as infrastructure of households). The Consumption Footprint has been the first attempt to build an EU-scale LCA model of consumption with a high level of granularity (e.g., consumption area, product group, RP, life cycle stage), therefore enabling the assessment of scenarios concerning not only changes in consumption patterns (e.g., decreased consumption of certain products, change in dietary patterns) but also of eco-innovations (e.g., technological, organisational, behavioural modifications along the supply-chain of products). This indicator builds however upon EU-wide country-scale statistics and has not yet been implemented at the city level.

1.2. Goal and scope

The goal of this paper is to assess the environmental impacts of the consumption of an average Turin citizen in 2018 by implementing the Consumption Footprint indicator at the city scale. Specific objectives aim to (a) explore the implementation of the Consumption Footprint indicator at the city scale, (b) discuss the advantages and challenges of using local and regional data, and (c) identify possible implications in decision-making and local policy development.

2. Methods

This section introduces Turin as a case study, the calculation of the consumption intensity of Turin citizens and the life cycle modelling underpinning impacts at the product level.

2.1. Case study: Turin (Italy)

Turin is the metropolitan centre of the Piedmont region (northwest of Italy) and is the 4th most populated Italian city, with a resident population of 879 004 inhabitants in 2018 (Istat 2020a). Trends indicate that one-person-households increased from 30% (2016) to 46% and the average number of family members was reduced by more than 30% in almost 30 years (i.e., from 2.77 in 1990 to 1.95 in 2019) (Urban Center Metropolitano 2018). The urban structure of Torino was influenced by its role in industrial development, hosting relevant manufacturing companies since the 1950s. With industries being nowadays in disuse, the municipality is currently defining a new image of the city focusing on sustainable development and innovation, in close cooperation with surrounding territories, universities and companies. Some sustainable practices arose in last years, such as the Torino City lab launched in 2018 aiming at connecting different stakeholders (e.g., public administration, companies) to boost innovative urban experimentation (Cuomo, Lambiase & Castagna, 2021). Additionally, in the recent review of the general city masterplan, the Turin municipality included the implementation of a multicriteria decision-making tool for the evaluation of the sustainability level of the city (Torabi Moghadam, Genta, Pignatelli, & Lombardi, 2020).

This case study has been selected due to (a) the size of the city: being one of the most important metropolitan cities in Italy, (b) data availability at the city level for different areas of consumption, and (c) the increasing trend for sustainable practices related to circular economy in this city.

2.2. The consumption footprint of an average turin citizen

This study assesses the environmental impact of Turin citizens by means of the Consumption Footprint indicator. The evaluation follows a product perspective, thereby integrating flows on resource use and emissions to the environment within the life cycle of the products. As well, the product-oriented modelling allows to have a consumption-oriented perspective. Compared to available methods and other approaches (e.g. urban metabolism, multi-regional input-output), the Consumption Footprint has been selected due to the (a) availability of data at national and EU levels, (b) granularity of the indicator, (c) broad coverage of environmental pressures, (d) assessment at impact level, and (e) life cycle perspective. Operationalizing the Consumption Footprint to the city-level of Turin followed three steps (Fig. 3): a) data sources identification; b) consumption patterns calculation, and c) impact assessment.

2.2.1. Identification of data sources

The main challenge of operationalizing the Consumption Footprint to the city level was identifying local data sources to calculate the consumption intensity of each RP for an average citizen. The selection of the data sources was performed according to two main criteria: (a) geographical scale, following a priority from most specific to less specific (i.e., city – region – country); and (b) data granularity, to maximize an alignment with the product composition of the Consumption Footprint. When city or regional data were lacking, the consumption intensity of an average Italian citizen was employed. When using national or regional data, downscaling was followed through an egalitarian approach by considering the same consumption intensity amongst the entire territory and assuming that the per capita consumption could be considered for the average Turin citizen. A complete list of RPs included in the evaluation and data sources used is reported in Supplementary Material (SM) (Tables SM1 and SM2).

Concerning housing, information about the construction period, energy and water consumption were accounted for at the city level. The construction period was evaluated using GIS (Geographic Information System)-based census data of 2011 (Istat 2011), which are annually updated in a regional database (Regione Piemonte 2021a) including recent building projects. Local electricity and heat consumption data were available in the regional open data platform (Regione Piemonte 2021b). Domestic water consumption was retrieved from urban statistical data (Istat 2018).

Data on mobility with private vehicles (by fuel, emission standards and engine capacity) were retrieved from a statistical report on Italian metropolitan cities (Istat 2018) and data on local public transport from the annual sustainability report of the local company (by fuel type) (GTT 2018).

Consumption data in terms of mass are rarely surveyed by cities and regions limiting the availability of data for the areas of consumption of food, household goods and appliances. In these cases, statistical local data (CCT 2019), regional surveys about family expenses (Istat 2019) and consumption behaviour (Istat 2020c) were combined. However, for a few RPs the average Italian consumption was retrieved from the Prodcom database (Eurostat 2021a), calculated as the apparent

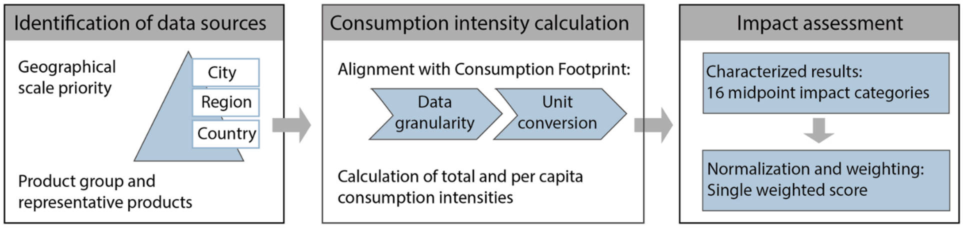

Fig. 3. Methodological steps for the regionalization of the Consumption Footprint to the city-scale.

consumption (i.e., production + imports – exports). As a general rule, when both local and regional data were available, local data were selected even with more limited granularity at the RP level, and regional data were employed for data adjustments (e.g., disaggregation).

2.2.2. *Modelling of consumption patterns*

Once data sources were identified for each RP, consumption intensities were calculated, i.e. the consumption of a given RP by an average Turin citizen for the reference year 2018. In this step, data calculations were required for alignment with the Consumption Footprint in terms of product granularity (e.g., adding level of detail) and unit of measurement (e.g., converting monetary values into mass). The consumption intensity calculation is described for each area of consumption.

2.2.2.1. Housing. This area of consumption includes three different elements: building infrastructure, energy consumption, and water consumption. Building infrastructure is classified amongst 8 different archetypes based on building type (single-family house (SFH) or multi-family house (MFH)), and construction period (<1945, 1945–1969, 1970–1989, >1990) (Baldassarri et al., 2017). Although the EU-level Consumption Footprint includes 24 archetypes differentiating amongst three thermal zones (cold, moderate, and warm), only those archetypes associated to the moderate climate zone were considered for Turin in line with its geographical location, with 2 450 Heating Degree Days (Arpa Piemonte 2021). To classify the Turin building stock in the 8 different archetypes, GIS census data of 2011 (Istat 2011) were used.

$$Consumption\ intensity\ _{RP}(kg) = \frac{Monthly\ expense_{PG,\ city}\ (\notin)\ *\ \frac{Monthly\ expense_{RP,\ region}}{Monthly\ expense_{PG,\ region}}(\%)}{Price_{RP}\left(\frac{kg}{\backslash euro}\right)} * \frac{Overall\ cons.\ (\notin)}{Covered\ cons\ (\notin)} \quad \text{(Eq. 1)}$$

Both domestic energy (Regione Piemonte 2021b) and water consumption (Istat 2018) were compiled at the city level and allocated equally amongst the Turin population.

2.2.2.2. Mobility. Mobility consumption included the use of different means of transport by the local population both for local commuting and extra-urban travels: private car, motorcycle, urban and extra-urban buses, train, and aeroplane. The number of private vehicles in use (Istat 2018) was multiplied by the average travelled km to obtain annual vehicle kilometres (vkm) which represent the annual km travelled by the vehicle. Annual vkm for public transport were retrieved from the sustainability report of the public transport company (GTT 2018). The local use of electric trams and subway were modelled as electric trains as a proxy. Extra-urban trips by aeroplane, train, or coaches are not monitored locally and Italian average data (EC-JRC, 2021) were used for these vehicle types which are measured considering km travelled by users using the passenger km unit of measurement (pkm).

2.2.2.3. Food. Food consumption data in terms of mass were not available and multiple data sources at different geographical levels were combined for estimating the consumption intensity for each RP (Eq. (1)). First, city-level data were retrieved from an annual survey reporting monthly expenses of families per product group (PG) (CCT 2019). Second, ISTAT data at the region level reporting monthly expenses of families per RP and PG were employed to identify the allocation of the expenses to individual RPs within each PG (Istat 2019). Local data excluded some RPs (e.g., tofu, sugar, almonds, biscuits, chocolate), for which the average expense per person at the regional level was used. Finally, the average price of the product was employed to transform expenses into mass values. Consumer prices were preferably used (Istat 2020b) and complemented with average prices from a market survey made by authors or bulk local prices (Ismea, 2019, 2021). Consumption intensity for each RP was upscaled to represent overall food consumption expenses (180,97 € per person per month) as covered RPs represented food expenses partially (158,64€ per person per month), based on local data (CCT 2019).

2.2.2.4. Household goods. City-level data were not available for household goods consumption. Regional data on monthly expenses were limited to PGs detergents, personal care products, and paper products (Istat 2019) without granularity at the product level. Similar to food products, regional data were combined with national data to allocate the expenses at the PG level to each RP (Eq. (2)). Price data were employed to obtain consumption intensity in terms of mass or pieces, based on a market evaluation of average consumer prices by authors. National average consumption data (Prodcom) were used for the remaining PGs due to lack of local data.

$$Consumption\ intensity\ _{RP}(kg) = \frac{Monthly\ expense_{PG,\ region}\ (\in)\ *\ \frac{Monthly\ expense_{RP,\ country}}{Monthly\ expense_{PG,\ country}}(\%)}{Price_{RP}\left(\frac{kg}{\in}\right)} \quad \text{(Eq.2)}$$

2.2.2.5. Appliances. Consumption of appliances is linked to household possession. The consumption intensity of appliances was calculated based on regional data on the number of households (Istat 2020a), possession share, average possession of a given appliance per household (Istat 2020b), and average lifespan (Reale et al., 2019) (Eq. (3)). Regarding lighting, no data were available and national consumption data were calculated (Prodcom).

$$Consumption\ intensity\ _{RP}(p) = \frac{N^{\circ}\ households\ (n) * \ Possession\ share_{RP}\ (\%) * \ Average\ possession_{RP}\ \left(\frac{p}{n}\right)}{lifespan\ (year)} \quad \text{(Eq. 3)}$$

2.3. Life cycle modelling of representative products and impact assessment

Collected data on consumption per citizen in Turin determined the consumption intensity of each of the RPs composing the Consumption Footprint. A LCI with a cradle-to-grave perspective was compiled for each RP towards modelling the environmental pressures of consumption. The LCI was composed by employing different data sources, including Product Environmental Footprint pilots (EC 2013), EU Ecolabel background studies (EC-JRC 2017) and literature. The commercial LCI databases ecoinvent v3.6 (Wernet et al., 2016) and agrifootprint 5.0 (Blonk Consultants 2019) were employed for background LCI data. In the case of electricity, the electricity mix of Italy for 2018 was modelled based on Eurostat 2021b. The LCI model of the Turin case study was characterized, normalized and weighted using the Environmental Footprint 3.0 method (EC-JRC 2018; Fazio et al., 2018). The 16 impact categories of the EF 3.0 method include Climate change (CC), Ozone depletion (ODP), Human toxicity, non-cancer (HTOX_nc), Human toxicity, cancer (HTOX_c), Particulate matter (PM), Ionising radiation (IR), Photochemical ozone formation (POF), Acidification (AC), Eutrophication, terrestrial (TEU), Eutrophication, freshwater (FEU), Eutrophication, marine (MEU), Land use (LU), Ecotoxicity freshwater (ECOTOX), Water use (WU), Resource use, fossils (FRD) and Resource use, minerals and metals (MRD). A single weighted score was calculated employing the EF global normalization factors (adapted from Crenna, Secchi, Benini & Sala, 2019) and the EF weighting set (Sala, Cerutti & Pant, 2018). The overall environmental impact of the consumption patterns of a Turin citizen in 2018 was assessed against the EF-based Planetary Boundaries (PBs) developed by Sala, Crenna, Secchi and Sanyé-Mengual, (2020), as science-based ecological thresholds. The life cycle impact assessment step has been performed with Simapro 9.0 (Pré Consultants, 2020).

3. Results

This section reports the main findings of the study including the consumption pattern of an average Turin citizen, and the resulting environmental impacts and hotspots.

3.1. Consumption intensity

Analysing the consumption intensity by product allows identifying hotspots of consumption (SM Table 3), as basis for interpreting the associated environmental impacts. Food consumption in terms of mass was dominated by beverages, vegetables, and fruits (21%, 17%, and 15% of the food category), with the lowest consumption associated to nuts, legumes, and tea and coffee. Household goods consumption was dominated by paper products (40%) in terms of mass, and by textile products (mainly due to T-shirts) in terms of pieces. On the contrary, bed mattresses were the least consumed ones probably because of their extended lifespan. Regional data from surveys were used to evaluate the consumption of appliances, where basic kitchen appliances are owned almost by every household (100% for the refrigerator and 98% for the oven). Final consumption was dominated by light bulbs associated to a short lifespan and higher renovation rates. Air conditioning, dishwashers and electric ovens were the least consumed ones.

Turin building stock is mainly composed by MFH (86%) as expected in a high population density urban agglomeration. Around half of the houses were built during the Italian economic boom (1945–1969), while recent construction was scarce (4%) partially caused by the economic crisis of 2008 and by the stable number of inhabitants. A comparison of the Turin building stock composition with the Italian one is reported in the SM-Fig. 1. Energy and water consumption for housing purposes were measured at the local level, with some data sources with high spatial resolution (e.g., district heating). An average Turin citizen consumes around 1000 kWh of electric energy, 3170 kWh of thermal energy and 70 m^3 of tap water.

Local mobility was dominated by the use of private vehicles with gasoline and diesel passenger cars reporting the highest rate of consumption in terms of Vkm (46% and 39%, respectively). Electric and hybrid vehicles were the least used means of transport (0,77% of total Vkm) together with local public buses (0,46%). Regarding extra-urban mobility, air mobility represented 80% of extra-urban pkm, especially concerning extra-EU flights, while mobility by coach had a marginal role (0,1% of total pkm of extra-urban mobility).

3.2. Environmental impacts of the consumption pattern of an average turin citizen

The overall environmental impact of the consumption patterns of a Turin citizen in 2018 was assessed against the PBs (Fig. 4). Turin citizens currently transgress the safe operating space for humanity of five impact categories (PM, ECOTOX, CC, FRD and MRD), and remains in the uncertainty area for one (FEU). These results are in line with the assessment of the consumption footprint at the EU-28 level (Sala et al., 2020). Comparing the environmental impacts of Turin citizens to the EU-28 average (EC-JRC, 2021) (Table 1), an average Turin citizen showed a larger impact for MRD (+36%), mainly due to a higher possession of appliances and for HTOX_c related to construction materials in households and the use of chemicals in furniture products. While ODP was 21% lower for an average Turin citizen, the largest differences were observed for IR (−46%), due to the different energetic mix of Italy and the lack of nuclear energy sources, and for FEU (−46%), because of different consumption patterns in certain products (e.g., seafood, furniture, construction materials, appliances). Compared to the average Italian citizen, different consumption patterns of Turin citizens lead to a lower environmental impact apart from MRD (+30%) and HTOX_c (+22%).

The analysis of the environmental impacts of consumption patterns at the city level allows observing trends related to SDG 12 about sustainable production and consumption at the goal level. The individual impact categories of the EF method are linked to five different SDGs: human health (SDG3), water (SDG6), climate (SDG13), marine

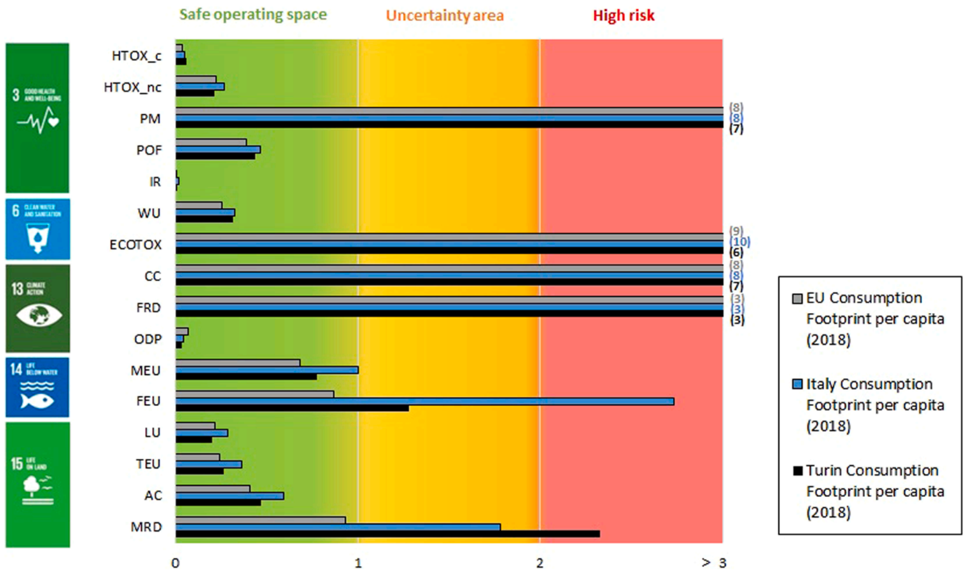

Fig. 4. Assessment of the Turin Consumption Footprint per capita (2018) against the EF-based PBs, and comparison with EU and Italian Consumption Footprint per capita (2018). The EF impact categories are relared to five different SDGs (EC-JRC, 2021).

Table 1
Consumption Footprint of average Turin, Italian and EU-28 citizen for 2018 (EC-JRC 2021).

Impact category	Unit	Turin (2018)	EU-28 (2018)	Difference	Italy (2018)	Difference
CC	kg CO_2 eq	$8.41\cdot 10^{3}$	$8.59\cdot 10^{3}$	98%	$9.78\cdot 10^{3}$	86%
ODP	kg CFC11 eq	$2.33\cdot 10^{-3}$	$2.95\cdot 10^{-3}$	79%	$3.25\cdot 10^{-3}$	72%
PM	Disease inc	$6.56\cdot 10^{-4}$	$7.23\cdot 10^{-4}$	91%	$8.87\cdot 10^{-4}$	74%
IR	kBq U^{235} eq	$4.70\cdot 10^{2}$	$8.71\cdot 10^{2}$	54%	$1.07\cdot 10^{3}$	44%
POF	kg NMVOC eq	$2.57\cdot 10$	$2.41\cdot 10$	106%	$2.72\cdot 10$	94%
AC	molc $H+$ eq	$6.79\cdot 10$	$7.33\cdot 10$	93%	$8.60\cdot 10$	79%
TEU	molc N eq	$2.31\cdot 10^{2}$	$2.68\cdot 10^{2}$	86%	$3.20\cdot 10^{2}$	72%
FEU	kg P eq	1.07	1.98	54%	2.29	47%
MEU	kg N eq	$2.25\cdot 10$	$2.47\cdot 10$	91%	$2.90\cdot 10$	64%
WU	m^3 water eq	$8.26\cdot 10^{3}$	$6.61\cdot 10^{3}$	125%	$8.45\cdot 10^{3}$	98%
LU	Pt	$1.49\cdot 10^{5}$	$1.78\cdot 10^{5}$	84%	$2.17\cdot 10^{5}$	69%
FRD	MJ	$1.11\cdot 10^{5}$	$1.05\cdot 10^{5}$	105%	$1.21\cdot 10^{5}$	91%
MRD	kg Sb eq	$7.37\cdot 10^{-2}$	$5.44\cdot 10^{-2}$	136%	$5.66\cdot 10^{-2}$	130%
HTOX_c	CTUh	$7.94\cdot 10^{-6}$	$6.12\cdot 10^{-6}$	130%	$6.49\cdot 10^{-6}$	122%
HTOX_nc	CTUh	$1.24\cdot 10^{-4}$	$1.32\cdot 10^{-4}$	94%	$1.56\cdot 10^{-4}$	79%
ECOTOX	CTUe	$2.02\cdot 10^{5}$	$2.12\cdot 10^{5}$	96%	$2.40\cdot 10^{5}$	84%

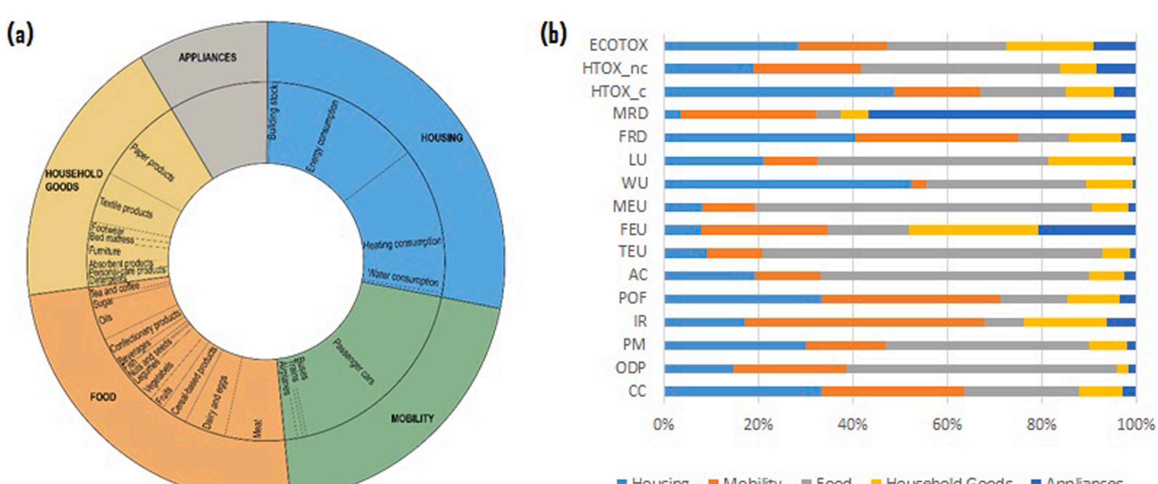

Fig. 5. Consumption Footprint of an average Turin citizen: (a) Contribution of areas of consumption and product groups to single score; (b) Contribution of the five areas of consumption by impact category.

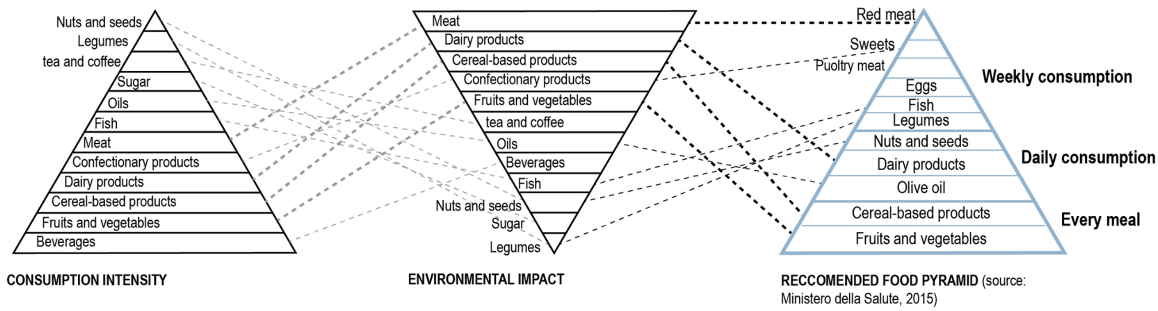

Fig. 6. Pyramids of food consumption, environmental per product and recommended food intake.

ecosystems (SDG14), and terrestrial ecosystems (SDG15). This LCA-based approach has a broader scope than current indicators for SDG target 12.2, where the material footprint is limited to evaluate the use of resources at the pressure level, by providing an assessment at the impact level and covering 16 different environmental aspects. Fig. 4 highlights that PBs associated to SDGs 3, 6 and 13 are transgressed, highlighting the relevance of addressing these environmental impacts in local policy-making.

3.3. *Hotspots: consumption areas, product groups and representative products*

The environmental impacts of the consumption patterns of a Turin citizen, as a single weighted score, were dominated by housing (28%), followed by food (24%) and mobility (20%) (Fig. 5a, SM – Table 4). Electric energy consumption was the main driver for housing consumption, accounting for 51% of the total impact while animal-based products (i.e., meat and dairy) and oils were the main drivers for food.

Housing was dominated by impacts due to energy consumption, with electric energy contributing to 51% and heating to 47%. Due to the geographical location in the Alpine region, Turin has high demands of energy for heating, however, the city is mainly connected to a district heating network, which is the largest network in Italy and a European best-practice fed by three efficient cogeneration plants (Guelpa, Barbero, Sciacovelli & Verda, 2017; Mutani & Todeschi, 2021). Impact due to the building stock was more limited (0.8% of the housing area), where the MFH built between 1945 and 1969 had the major role.

Although reporting a limited consumption intensity compared to other food products, meat and dairy products were the food products with the largest unitary environmental impact in the food area, contributing to 37% of overall food impacts. Vegetables and fruits resulted in an opposite situation, with a high rate of consumption intensity (more than 200 kg per person per year) corresponding to a lower share of the overall food environmental impact (14% for vegetables and fruits together). By comparing consumption intensities with corresponding unitary impacts, two opposite pyramids were identified where for some food products with a low consumption in mass correspond to a higher impact and for other a higher consumption intensity corresponds to a lower contribution in environmental impacts (Fig. 6). Additionally, comparing the environmental impact pyramid with the recommended food pyramid for Italy (Ministero della salute 2015) highlights that recommended food corresponds to low impacting food, and conversely for more impacting options.

Regarding mobility, impacts are in line with consumption patterns with gasoline and diesel passenger cars dominating the impacts (73%) and extra-EU flights having a relevant role (9% of mobility impacts). Electric and hybrid vehicles showed the lowest contribution (0.7%) due to not only limited consumption intensity but also low unitary impacts.

Paper products (44%), textile products (25%) and furniture (10%) were the most contributing product groups to household goods consumption. Clothes (particularly, T-shirts) and paper were associated to a high consumption intensity resulting in a higher environmental impact. Finally, appliances consumption reported the lowest impact (9%) driven mainly by TV screens, mobile phones, and tumble dryer. However, note that the role of appliances is expected to be higher since the electricity consumption during the use phase of appliances was accounted for as part of the overall electricity consumption of households in 'Housing' to prevent double-counting.

Areas of consumption contribute differently to the 16 impact categories of LCA (Fig. 5b). Food impacts were dominant in impact categories related to agriculture (e.g., LU, MEU, TEU, AC, ODP), mobility was the main driver for impacts associated to energy consumption and fossil fuels combustion (e.g., IR, POF), housing impacts were predominant in health impact categories (e.g., HTOX_c, HTOX_nc, ECOTOX) and WU, and impacts due to appliances consumption mainly referred to resource use (e.g., MRD). The contribution of different areas of consumption to the different impacts is aligned to results at the EU level (Sala et al., 2019b). Note that the role of the different life cycle stages of products are strongly associated to the area of consumption and impact category (Sala et al., 2019a). For example, upstream activities are very relevant for food and household goods in most of the categories, while the use phase is often the major contributor for mobility, housing and appliances. Some impact categories show particular behaviours, such as the role of upstream activities for appliances in the category resource use, minerals and metals, as well as the role of logistics of food in ozone depletion.

4. Discussion

In this section, challenges and obstacles related to the collection of data at the local level are discussed, together with relevant harmonization and integration issues.

The evaluation of the Consumption Footprint of a city posed some challenges, especially concerning data collection and analysis due to the use of multiple data sources with different levels of disaggregation. Firstly, some areas of consumption were not monitored at the local level (e.g., household goods), requiring the use of data at regional or national level and its integration with local information when possible. Combining data from different geographical scales was useful also to compare local patterns with regional or national trends. For most food products local aggregated data of food expenses were combined with more disaggregated information of regional average expenses. Consequently, it was possible to identify similarities and differences between Turin urban context and regional averages. As an example, monthly food expenses of Turin households for dairy, fruits, and cereal-based products are similar to the regional average; while household consumption of alcoholic beverages, fish and meat in the city is significantly lower than the regional average. This suggests that urban areas are more associated to sustainable and healthy choices in food purchasing. Some scholars indicate that more environmentally-friendly patterns can be associated to better social and economic conditions (Davidescu, Apostu & Paul, 2020; Ortega-Egea, García-de-Frutos & Antolín-López, 2014), which are more likely in urban areas.

Secondly, the combination of multiple data sources or the need to convert units (e.g., from economic value to mass through product price) increased data uncertainty. Although local data at the PG level were available in some cases (e.g., food), the calculation of the environmental impact of consumption was considered more robust when disaggregating the consumption intensity by RP although this was performed by combining data from different geographic scales. The choice of combining data at different scales when necessary was taken as the environmental impact of RPs within the same PG can vary consistently (e.g., amongst household goods product, Castellani et al., 2021) and therefore quantifying the impact of the consumption of each RP can minize the uncertainty in calculating the impacts of the entire PG. To minimize the impact of unit conversion, consumer price statistics or observed prices in the local market were employed.

Thirdly, the local scale offered the opportunity to work with very detailed data, e.g. GIS data. For housing, energy consumption (district heating) and construction period were reported at the district level, enabling a higher spatial resolution to identify and compare geographical hotspot of consumption (e.g., the role of different neighbourhoods). Using georeferenced data for evaluating environmental impacts have been explored mainly in the energy building sector, e.g., district level household energy consumption in Lima (Perú) (Cárdenas-Mamani, Kahhat & Vázquez-Rowe, 2022), or regarding consumption patterns of water consumption (e.g. Tabriz city, Iran; Feizizadeh et al., 2021). GIS data allows for adopting a bottom-up approach that can characterize local attitudes and develop transformation scenarios (Monzón-Chavarrías, Guillén-Lambea, García-Pérez, Montealegre-Gracia & Sierra-Pérez, 2021) or can support local decision-making by including consumption data and other context-related indicators and parameters (Torabi Moghadam, Genta, Pignatelli, & Lombardi, 2020). Such level of analysis can also be employed to link environmental data with data representing parameters underlying the spatial variability of consumption patterns (e.g., spatial configuration, socio-demographic and consumer characteristics, or building infrastructure) (Voskamp, Visscher, Vreugdenhil, Van Lammeren & Sutton, 2021).

Finally, although the implementation of the Consumption Footprint to the city scale was in general satisfactory, specific aspects were identified for further improvement regarding the composition and the underpinning LCI data of the model. On one hand, some products reported in local statistics (e.g., public transport like metro) were not considered as individual representative products and a proxy was employed. Involving local stakeholders to identify missing representative products might shed light on required efforts for more accurate implementations. With emerging sustainable behaviours, the inclusion of new products based on different production options could support the analysis of the consumer footprint of specific individual behaviors. On the other hand, the LCI model was compiled to represent the EU average market (i.e., not aligned to the local context) as done for the Consumer Footprint Calculator, a user-friendly tool for the assessment of the specific consumption pattern of EU citizens (Sala, De Laurentiis, Barbero Vignola, Marelli & Sanyé Mengual, 2022). In this study, the electricity mix of Italy was modelled to better represent the technological context for the city of Turin. Further efforts could focus on regionalizing the LCI models for specific products where the geographical context is more significant or affecting transversal processes amongst different areas of consumption (e.g., waste treatment, wastewater treatment, energy mix).

6. Conclusions and further research

Evaluating the Consumption Footprint of citizens is a necessary step in the definition and monitoring of the contribution of cities to the implementation of CE and sustainability principles. Assessing the environmental impact of consumption patterns at city level is still limited, although cities have a crucial role in decision-making processes and policy development, which calls for the integration of different sectors for the sustainable development of cities and territories. Simultaneously, cities can be drivers for innovation and transition toward a more circular and sustainable development, where welfare is maximised and impacts remain within ecological limits. For this purpose, the LCA-based Consumption Footprint indicator can support local policies and this study represents the first attempt on implementing this indicator to the city level.

The Consumption Footprint of the average Turin citizen for the year 2018 was in line with average impacts per capita at national and European level but allowed observing local trends in consumption patterns and intensity. Housing and Food reported the highest share of impacts, driving impacts on CC and human health and wellbeing (e.g., HTOX_c, POF, PM). Main challenges of implementing the Consumption Footprint at the city scale were found in data collection (e.g., lack of data for certain consumption areas at local level, partial coverage of products), aggregation and harmonization (e.g., granularity and categorization of products), and transformation (e.g., units). Furthermore, the implementation of a case study revealed some room for improvement of the Consumption Footprint to better model the urban context (e.g., limited coverage of urban public transport like subway or trams).

Overall, this study contributes to the literature regarding the assessment of the environmental footprint of cities from a consumption perspective, the development of LCA and the use of LCA-based indicators at the city scale, and the discussion on indicators for assessing and monitoring local policies and initiatives. This work may underpin a number of research developments, for example related to assess impacts at different scales, e.g. at the neighbourhood level, compiling consumption data through local survey for missing products or regionalizing LCI data. Furthermore, being the consumption footprint complementary with urban metabolism approaches, it could be of interest to explore synergies between these types of assessment towards more comprehensive policy support at city scale, addressing resource-specific as well as impact-specific aspects. Moreover, impact results could be evaluated at the damage level towards understanding the contribution of the individual citizen to, for example, biodiversity loss. At the EU level, consumption impacts at the endpoint highlight the critical role of food (57%) regarding biodiversity loss (mainly due to land use and climate change), and of housing (32%), food (29%) and mobility (22%) regarding human health (mainly because of climate change and particulate matter) (Sala et al., 2019b). Further research is needed to enable the use of the Consumption Footprint at city level in a transdisciplinary setting, i.e., through the involvement of local stakeholders for better addressing local consumption patterns and trends and to expand the representative products used in the model .

Declaration of Competing Interest

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

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Supplementary materials

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