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Additives in the food supply chain: Environmental assessment and circular economy implications

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ABSTRACT

Food additives constitute an integral ingredient of food production and processing operations, as their functional properties are paramount to not only improving the organoleptic qualities but also preventing spoilage thus prolonging food products' shelf life. Despite their cardinal role in the food industry as key facilitators of global food supply and distribution, aspects related to the food additives supply chain remain an underdeveloped research area. Using as a case study a food processing company in Greece that specialises in the production of meat additives, the objective of this paper is twofold. First, to assess the environmental performance of the company's production process, identifying the main hotspots and drivers for environmental impacts by means of the Life Cycle Assessment method. Second, following the identification of employed circular economy practices, to discuss corresponding managerial implications. The latter will attempt to contribute to the enrichment of circular economy in the context of food supply chains relevant literature through exploring strategies of reducing meat additives surpluses, shading light on the underexplored yet paramount industry between the stages of food production and processing. In addition, some social considerations based on the obtained Life Cycle Assessment results will be given, to discuss the consequences of productive behaviours and to understand how they perform in the national context.

1. Introduction

Urbanisation and globalisation along with the ongoing socio-economic changes have triggered a spiral of broad and rapid shifts in consumption patterns, deeply transforming global food supply chains (Popkin, 1999, 2006, 2014). Over the past decades, the world has been experiencing a significant dietary transition characterized by increased levels of meat consumption, as a consequence of increasing trends in middle income countries (e.g., China, East Asia) opposing to decreasing trends in high income countries (Godfray et al., 2018). Driven by a diverse set of socio-economic, cultural, and geographical factors (Milford et al., 2019), the global consumption of meat almost doubled, surging from 23.1 kg in 1961 to 42.9 kg per capita/year in 2018 (FAOSTAT, 2021). At the same time, the global production of meat nearly quintupled, exceeding 342 million tonnes per year (FAOSTAT, 2021). According to OECD-FAO's (2020) latest agricultural outlook report, livestock production is projected to record a twofold increase of 14% by 2029, implying a 6% growth in agriculture's direct emissions. While constituting an important part of a typical diet as a pivotal source of high-quality proteins and vitamins, meat's rich nutrient composition of high-water content and ideal pH levels make it an ideal environment for the rapid growth and propagation of spoilage microorganisms (Nair et al., 2020), which may result in the development of uncharacteristic odours and flavours, changes in colour, risks of foodborne disease occurrences, as well as economic losses. As a consequence, the quality of meat products demonstrates a rapid rate of deterioration from harvest to consumption. This rate depends on different interrelated factors, mainly pertaining to storage conditions (e.g., temperature, light intensity, moisture, density, holding time) and intrinsic meat properties related to enzymes and microorganisms. Therefore, in order to maintain the

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quality and ensure the microbiological safety of meat products, efforts are concentrated on halting the microbial growth along all stages from production to processing, handling, and household consumption.

Food additives constitute an integral ingredient of modern food production and processing operations, as their functional properties are paramount to not only improving the organoleptic qualities but also preventing spoilage thus prolonging food products' shelf life (Griffiths and Borzelleca, 2014). According to the FAO/WHO (2021) Codex Alimentarius, a food additive is defined as "any substance not normally consumed as a food by itself and not normally used as a typical ingredient of the food, whether or not it has nutritive value, the intentional addition of which to food for a technological (including organoleptic) purpose in the manufacture, processing, preparation, treatment, packing, packaging, transport or holding of such food results, or may be reasonably expected to result, (directly or indirectly) in it or its by-products becoming a component of or otherwise affecting the characteristics of such foods". There are six main types of food additives: preservatives, nutritional additives, colouring agents, flavouring agents, texturizing agents, and miscellaneous agents (Carocho et al., 2015). Specifically, processed meat is among the foods that most heavily rely on synthetic preservatives. Nowadays, food additives constitute an indispensable ingredient of a wide spectrum from minimally to highly processed foods. Given that 75% of the Western diet consists of processed foods, estimates place the average additives consumption to at least 3–4.5 kg per year (Zengin et al., 2011).

While their use is paramount to maintain a high standard of variety and supply safety, the chemical nature of their majority has raised increased concerns regarding the safety of their consumption (Carocho et al., 2015). Food safety constitutes the prevalent topic in the food additives literature, mainly due to instances of their abuse and illegal use of chemical ingredients (Wu, 2021; Van de Brug et al., 2014). Extant research has been largely performed within the field of food chemistry and biochemistry, involving food safety assessment and detection methods (Sun et al., 2021; Kosek et al., 2019; Mohammadzadeh-Aghdash et al., 2018), related methodological evaluations (Kabadi et al., 2019), food engineering (Zhang et al., 2020; Mokni Ghribi et al., 2018), and toxicity studies (Tasaki et al., 2008). Food ethics also constitutes another point of substantial interest, examining the potential consumer health risks associated with food additives (Felter et al., 2021) and consumer sovereignty (Jansen et al., 2020; Aoki et al., 2010). Given the interplay between food ethics and behaviour pertaining to the consumers' base of judgement on their trust in respective regulatory bodies (Eiser et al., 2002), many studies examine consumers' perceptions and preferences towards food additives with respect to healthy attributes and sensory properties (da Conceição Jorge et al., 2015; Bearth et al., 2014). The regional focus is evident within the literature, owing to the variability in the occurrence frequency and severity of food safety incidents as well as in the different perceptions about additives across countries. In addition, there is a dearth of publications that adopt a supply chain perspective. Partly exceptions are Song and Zhuang (2017) game-theoretical model on government, manufacturers, and farmers' interactions to study optimal risk management policies and Wu et al. (2013) case survey regarding the critical factors influencing the use of additives by food enterprises in China. Nevertheless, the food safety aspect is prevalent in both papers, approached from a risk perspective. The recent growing research interest in the circular economy has developed a novel literature stream, focusing on the potential recovery and utilisation of agro-waste and by-products for the production or their direct use as natural food additives (Onur et al., 2019; Galanakis, 2018; Quina et al., 2017; Jurgilevich et al., 2016; Rakicka et al., 2016). Several Life Cycle Assessment (LCA) studies of respective recovery processes are also included in this stream (Monteiro et al., 2020; Pérez-López et al., 2014). Similar to the main body of extant literature, these papers have a micro-level focus and restrict their analysis on the biotechnological methods and processes used to achieve the recovery of required compounds for the production of food additives.

Despite their cardinal role in the food industry as key facilitators of global food supply and distribution, aspects related to the food additives supply chain remain an underdeveloped research area. Food supply chain-related research mainly focuses on final food products, rather than on their raw materials ingredients, and respective processes involved in their production. FAO's 2021/2022 projections for an expansion of food commodities output, with meat production anticipating a 2.2 percent increase (346 million tonnes) (FAO, 2021), indirectly entails an equivalent growth of food additives.

To address this gap, a food processing company in Greece that specialises in the production of meat additives is used as a case study. The aim is twofold namely, to assess the environmental performance of the company's production process using the LCA method and successively to discuss related managerial implications related to employed circular economy practices. This study constitutes an attempt to enrich the emerging circular economy in the context of food supply chains relevant literature through exploring strategies of reducing meat additives surpluses, in so investigating the overlooked yet paramount industry between the stages of food production and processing.

The performed interpretation of LCA results in a social perspective responds to the necessity to adopt a multicriteria framework for the study, being food supply chain characterized by a complexity which requires such a diversified approach, both for market reasons and for decision-making perspectives. This need is linked to the growing attention of customers to the producers' performances and by the necessity to regulate productive behaviours towards wider sustainability (Petit et al., 2018). Moreover, it is widely recognized that social aspects are often neglected compared to environmental ones (Messmann et al., 2020).

Social sustainability assessment is still a developing field and includes topics such as social justice, human rights, discrimination, and child labour (Eskandarpour et al., 2015). Aiming not at performing a proper social sustainability assessment, this article provides a social interpretation of environmental LCA results, thus opening the possibility to widen the social sustainability perspective in future studies. This is performed by taking into account selected environmental LCA-derived indicators which could be used to analyse human behaviours and their connection to lifestyles, as the carbon and environmental footprints, comparing them to the national Greek levels in order to understand how the investigated case study participates in the general "wellbeing" of the nation. The existing correlation between environmental impacts and social welfare is becoming more and more recognized as of paramount importance to overcome the current, unsustainable, growth paradigm (Fioramonti et al., 2022).

2. Material and methods

2.1. Case study description

The examined company is a third-generation family-owned SME business of 19 employees in the city of Thessaloniki (Greece), which operates more than 50 years. Starting its activity as a potato starch trader in the meat industry, the company extended its technical knowledge and evolved into a food processing company that specialises in the production of food additives. Its final products mainly involve multicomponent dry mixes for meat products including starches, condiments, proteins, preservatives, stabilisers, and marinades. Apart from its head office, production plant and warehouse facilities, the company has its own R&D testing laboratory which enables it to develop new product or improve existing ones. According to the data, 86% of the company's raw materials are sourced from abroad, 72% from within the EU and 14% from the rest of the world. On the other hand, the largest base of their customers is located domestically (75%) while the remaining production (25%) is exported to other EU countries.

Fig. 1 provides an overview of the different steps within the company's production process. This flow chart was provided by the

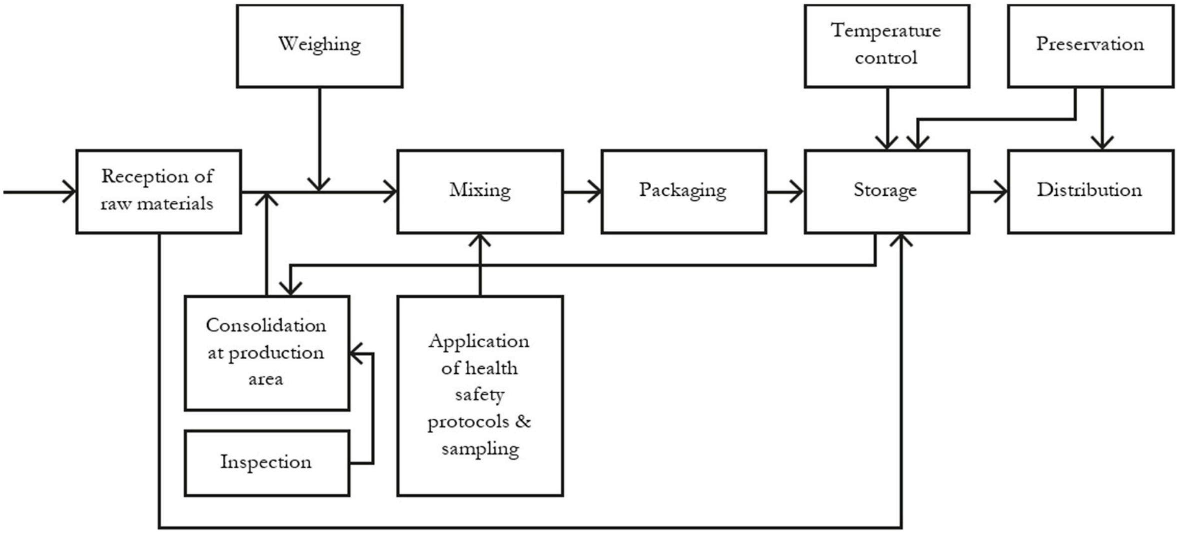

Fig. 1. Overview of the company's production process.

company as part of the documentation for ISO 9001 and ISO 22000 accreditations. The core of the process involves five main steps, namely reception, mixing, packaging, storage, and distribution. Once the raw materials are received, part of them is stocked in a small warehouse next to the production area while others, depending on their properties, are moved to a temperature-controlled storage room. Prior to the beginning of the production process, the ingredients listed on the production sheet for each final product are consolidated and subsequently inspected to evaluate their quality. Those that do not meet the required specifications are eliminated as are likely to cause trouble during the mixing stage. After ensuring that all requirements are met, the next step involves the weighing stage, to specify the quantity of the ingredients needed for each product. Weighing takes place using five customised electronic accuracy scales since minor deviations from the production sheets have a direct effect on the final products' taste, colour, clarity, and odour. The preparation phase is followed by the mixing stage which is conducted batch-wise using two customised stirring machines that can adapt for numerous mixing tasks according to the type of each mixture. Once the mixing process is finalised, the dry mixes are packaged in paper bags while colourants, which constitute a very small portion of the total production, are filled in plastic bottle containers. All final products are stored in a temperature-controlled room until their dispatch for delivery to the final customers.

2.2. *Data collection*

A combination of primary and secondary data was used for this case study. Primary data was related to the company's production process, its stages, relationship with suppliers and customers, causes of waste, implemented circular economy practices and factors that inhibit the adoption of the latter. This was collected through weekly face-to-face joint interview sessions over the span of two months with both the Quality Assurance and R&D Manager and the Purchasing Manager. Each of these interview sessions lasted for 30–45 min and was based on open-ended questions based not only on the predetermined key topics but also on points that were raised in previous sessions and required further clarification. On the other hand, secondary data was related to the information required for performing LCA. A total of 128 raw materials and 178 final product categories were collected. To ensure disclosure compliance with respect to the final product mixes, raw materials and final products were grouped into twelve and four categories respectively. Grouping inputs and outputs in the manuscript were necessary due to confidentiality concerns raised by the company since the ingredients of each mix constitute a core part of their competitive advantage. A summary of these categories along with respective abbreviations can be found in Table 1.

2.3. *Life Cycle Assessment*

Life Cycle Assessment (LCA) is an environmental assessment method defined by ISO standards (ISO, 2006a; 2006b) as a four steps tool for the investigation of potential environmental impacts and resource depletion related to human dominated processes in a 'cradle to grave' approach, from resources extraction through production, use, maintenance, and final disposal of waste related to generated products and/or services.

Following ISO 14040 and 14,044, LCA is standardized into four main phases:

i. Goal and Scope definition, within which the reason behind the study, the context, system boundaries and Functional Unit (FU), among other aspects, are defined.
ii. Life Cycle Inventory (LCI) analysis, defining the system's input and output flows properly proportioned to the chosen FU.
iii. Life Cycle Impact Assessment (LCIA), representing the translation of the built inventory into environmental impact indicators through the selection of the investigated impact categories, the assignment of LCI results to the different impact categories (classification) and the calculation of results with the proper unit (characterisation). LCIA is usually performed by means of proper

Table 1
Classification of raw material inputs and final product outputs.

Type	Category	Abbreviation
Raw material inputs	Additives	ADD
	Avo supplier	AVO
	Breadings	BRD
	Chemicals	CMC
	Chemical liquids	CML
	Colourants	COL
	Fibre	FBR
	Milk	MLK
	Packaging	PAC
	Protein	PRT
	Spices	SPC
	Starch	STR
Final product outputs	Colourants	CLR
	Compi mixes	NCO
	Seasonings	NKR
	Blends	NMX

designed impact assessment methods, developed in order to be used together with LCA software and databases.

iv. Interpretation of results to understand and properly address the hotspots of the investigated case study.

An additional non-mandatory LCA step is the normalisation of results by means of proper normalisation factors, useful to calculate the magnitude of LCIA results with relation to reference information and to compare among the obtained unit-less normalised results. Normalised results are obtained dividing each characterized result by the related normalisation factor, to support the interpretation of the results of the study. Normalisation factors are built basing on vast amount of data about environmental impacts and resource extraction and represent the total impact on a global level or of a reference region for a certain impact category in a reference year. Therefore, the normalisation procedure allows for a better understanding of the relative magnitude for each indicator result of the product under study. The environmental impact assessment was performed using the SimaPro software v. 9.1.1.1 (Oele, 2020), including the Ecoinvent database v.3.7 (Wernet et al., 2016) and the 2016 ReCiPe 2016 Midpoint v.1.1 method (Huijbregts et al., 2017), to obtain a set of characterized results with the proper unit and a World (2010) Normalisation. The ReCiPe Midpoint impact categories are shown in Table 2. Taking into consideration all the categories calculated by the impact methods allow a comprehensive investigation of a complex system, such as the one studied in this work, characterized by an agricultural part and an industrial part, with very different environmental impacts in different compartments.

The FUs chosen for the investigated case study are the four final product categories (mass allocation proportional to the percentage of the company's total annual production), namely colourants – CLR (0.3%), compi mixes – NCO (14%), seasonings – NKR (9%), and blends – NMX (76.7%). Developing the assessment in terms of these four categories of products, aggregating the 178 different final product flows, is beneficial in terms of clarity and comprehensiveness of the LCA results, by presenting four sets of result instead of 178. CLR category products involve colourants used to maintain or enhance the colour properties of food products; NCO category products correspond to mixes that include both stabilisers and seasonings which are added to food to smoothen and preserve food structure; NKR category products are used to enhance flavours, intensifying the natural flavour of respective food products without altering it; NMX category products are usually referring to stabiliser mixes.

Table 3 summarises the input and output flows related to the production of the four category products.

Table 2
ReCiPe 2016 Midpoint H v.1.1 impact categories.

Impact Category	Abbreviation	Unit
Global warming	GWP	kg CO_2 eq
Stratospheric ozone depletion	ODP	kg CFC11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Ozone formation, Human health	OFHP	kg NO_x eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	OFTP	kg NO_x eq
Terrestrial acidification	TAP	kg SO_2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB
Human carcinogenic toxicity	HCTP	kg 1,4-DCB
Human non-carcinogenic toxicity	HNTP	kg 1,4-DCB
Land use	LUP	m^2a crop eq
Mineral resource scarcity	MSP	kg Cu eq
Fossil resource scarcity	FSP	kg oil eq.
Water consumption	WCP	m^3

Table 3
Inventories for the generation of the CLR, NCO, NKR and NMX category products.

Inputs	Outputs				
	Unit	CLR	NCO	NKR	NMX
Land Occupation	m^2a	1.50	68.70	44.00	380.00
Electricity	kWh	176.00	8291.00	5400.30	45,844.20
Machinery	kg	0.78	37.52	24.44	207.45
Water	L	893.00	–	–	–
ADD (Additives)	kg	–	9842.50	14,404.84	33,968.19
AVO (Avo supplier)	kg	–	6005.63	1161.16	35,351.57
BRD (Breadings)	kg	–	4797.02	–	3647.73
CMC (Chemicals)	kg	–	4019.91	454.22	71,643.10
CML (Chemical liquid)	kg	19.00	–	–	–
COL (Colourants)	kg	38.00	–	–	–
FBR (Fibre)	kg	–	127.99	–	2658.05
MLK (Milk)	kg	–	2066.78	–	5005.46
PAC (Packaging)	kg	120.06	1355.08	1003.68	3516.41
PRT (Protein)	kg	–	1025.18	–	25.49
SPC (Spices)	kg	–	8451.56	10,772.93	1036.57
STR (Starch)	kg	–	8426.22	299.22	94,174.25
Total	kg	950.00	45,308.60	29,155.80	248,130.70

2.4. Calculation of socio-environmental indicators

To fully study the impacts of food additives, we calculated some social indicators based on the LCA results. The indicators have been taken into account, namely:

- Carbon Footprint: Carbon footprint estimates the total amount of greenhouse gases emitted during the production, processing and retailing of consumer goods (Plassmann and Jones, 2010) expressed as amount of CO_2 equivalent;
- Environmental Footprint: Environmental footprint (also known as ecological footprint) considers the entirety of supply and demand of goods and services for the planet. In doing so, it is assumed that the environmental footprint of a certain population is in a way connected to, and thus representing, its lifestyle. The estimation of the environmental footprint starts with the calculation of the land, water, or sea area required to supply the food, housing, mobility, goods and services of a person in a certain region. The estimation is dependent on the area that the person resides. The reason is that ecosystems differ in their capacity to produce biological materials and to absorb CO_2. This is known as "biocapacity" (Swiader et al., 2019; Čuček et al., 2015);
- CO_2 emitted per m^2: The quantity of CO_2 which is emitted in each m^2 for the production of a good/service (Luo et al., 2016).

Calculated per capita data have been compared to Greek national indicators following some criteria to reach an acceptable approximation. Carbon Footprint and Environmental Footprint have been transformed in their correspondent per capita value dividing their total amount by an estimation of the number of people served by the investigated company. These indicators need to consider people according to their consuming activity, and have been calculated as in Eq. (1) where LCA_{ind} stands for LCA derived indicators (e.g. $CO_{2eq.}$ emissions and land occupation); TOT_{prod} indicates the company's total annual production and $CONS_{pc}$ is the per capita consumption of food additives

$$PerCapita\ indicator = \frac{LCA_{ind}}{\left(TOT_{prod}/CONS_{pc}\right)} \tag{1}$$

The estimation of how many people is served by the company's products has been calculated starting from the assumption that the average per capita annual consumption of food additives is 4.5 Kg (Zengin et al., 2011). Dividing the total amount of the annual production by this number, it is possible to obtain the estimation that allows to say that the company theoretically serves at least ≈72,000 people, assuming that these people only have an intake of additives from the investigated company. Of course, this number can only be bigger in reality, as people consume food additives from countless different sources. The per capita indications of CO_2 emitted per m_2 has been calculated by dividing the per capita carbon footprint by the per capita environmental footprint.

3. Results

Table 4 shows the ReCiPe Midpoint H characterized impacts related to the annual production of CLR, NCO, NKR and NMX products. NMX, being the largest annual production, represents an average 83% of total impacts among all impact categories.

As highlighted by the diagram in Fig. 2, the investigated system imports different kinds of additives, to be processed in four categories of products. The present works aim to assess, by means of LCA, the environmental burdens related to the investigated company annual production and to the disposal of the related packaging waste.

LCA results showcased the low environmental impact associated with the company's production process. This was accredited to the low energy consumption of involved equipment in each production stage; with the annual electricity consumption of the production facility averaging at less than 60Mwh. Out of the 4 final product categories, NMX followed by NCO were accounted for the highest environmental impact. However, this was related to the high amount of produced quantity of these categories. According to the results, the largest share of contribution to final impacts is always related to the components acquired by the company. Fig. 3(a–d), illustrate the percentage contributions to environmental impacts related to the production of CLR, NCO, NKR, and NMX respectively. An average of 40% contribution to CLR impacts (Fig. 3a) across all impact categories are related to packaging materials (PAC), while an average ~ 26% comes from electricity, ≈20% from COL, and ≈13% CML raw material categories. All the remaining contributions add up to an average of 2% across all impact categories. With respect to the NCO (Fig. 3b), the major impact is due to STR (≈34%), followed by AVO: (≈14%), CMC (≈13%), SPC (≈12%), electricity (≈10%), and BRD (≈10%). All remaining items contribute to impacts for a total of 7% in average. On the other hand, SPC is the major responsible for NKR impacts (Fig. 3c), with a contribution of about ≈47% across all categories. Other relevant contributions are related to ADD (≈16%), electricity (≈16%), CMC (≈9%), and PAC (≈5%). Regarding the environmental impacts related to the production of NMX (Fig. 3d), these are mainly attributed to STR (≈51%), CMC (≈23%), AVO (≈14%) and electricity (≈7%) while all other items show a contribution of total ≈5%. It is evident that the company's production process slightly increases the burdens generated by the industrial driven, and perhaps intensive processes to produce the raw materials used. Therefore, the burdens associated with the production of meat additives must also be considered when assessing the entire food processing sector and its sustainability. The distribution of the burdens mainly within the toxicity related impact categories, within LUP and within FEP, confirm how intensive agro-industrial processes can lead to specific environmental problems.

Table 4
ReCiPe Midpoint (H) characterized results for the generation of CLR, NCO, NKR and NMX food additive product categories.

Impact category	Unit	CLR	NCO	NKR	NMX	Total
GWP	kg CO_2 eq	$5.4\bullet10^{2}$	$6.1\bullet10^{4}$	$2.5\bullet10^{4}$	$4.4\bullet10^{5}$	$5.3\bullet10^{5}$
ODP	kg CFC11 eq	$2.3\bullet10^{-4}$	$2.8\bullet10^{-1}$	$1.2\bullet10^{-1}$	$1.8\bullet10^{0}$	$2.2\bullet10^{0}$
IRP	kBq Co-60 eq	$2.3\bullet10^{1}$	$2.0\bullet10^{3}$	$9.0\bullet10^{2}$	$1.5\bullet10^{4}$	$1.8\bullet10^{4}$
OFHP	kg NO_x eq	$1.2\bullet10^{0}$	$1.6\bullet10^{2}$	$7.0\bullet10^{1}$	$1.2\bullet10^{3}$	$1.5\bullet10^{3}$
PMFP	kg PM2.5 eq	$1.0\bullet10^{0}$	$1.2\bullet10^{2}$	$5.2\bullet10^{1}$	$9.3\bullet10^{2}$	$1.1\bullet10^{3}$
OFTP	kg NO_x eq	$1.3\bullet10^{0}$	$1.7\bullet10^{2}$	$7.5\bullet10^{1}$	$1.2\bullet10^{3}$	$1.5\bullet10^{3}$
TAP	kg SO_2 eq	$2.2\bullet10^{0}$	$4.3\bullet10^{2}$	$1.9\bullet10^{2}$	$3.3\bullet10^{3}$	$3.9\bullet10^{3}$
FEP	kg P eq	$4.9\bullet10^{-1}$	$3.9\bullet10^{1}$	$1.7\bullet10^{1}$	$2.6\bullet10^{2}$	$3.1\bullet10^{2}$
MEP	kg N eq	$4.8\bullet10^{-2}$	$6.3\bullet10^{1}$	$2.2\bullet10^{1}$	$4.7\bullet10^{2}$	$5.5\bullet10^{2}$
TETP	kg 1,4-DCB	$1.4\bullet10^{3}$	$2.7\bullet10^{5}$	$9.2\bullet10^{4}$	$2.3\bullet10^{6}$	$2.7\bullet10^{6}$
FETP	kg 1,4-DCB	$2.7\bullet10^{1}$	$3.8\bullet10^{3}$	$1.4\bullet10^{3}$	$3.5\bullet10^{4}$	$4.0\bullet10^{4}$
METP	kg 1,4-DCB	$3.7\bullet10^{1}$	$4.3\bullet10^{3}$	$1.7\bullet10^{3}$	$3.9\bullet10^{4}$	$4.5\bullet10^{4}$
HCTP	kg 1,4-DCB	$3.4\bullet10^{1}$	$2.8\bullet10^{3}$	$1.2\bullet10^{3}$	$2.6\bullet10^{4}$	$3.0\bullet10^{4}$
HNTP	kg 1,4-DCB	$7.9\bullet10^{2}$	$9.4\bullet10^{4}$	$4.7\bullet10^{4}$	$7.6\bullet10^{5}$	$9.1\bullet10^{5}$
LUP	m^2a crop eq	$2.1\bullet10^{2}$	$2.0\bullet10^{6}$	$3.8\bullet10^{6}$	$6.8\bullet10^{6}$	$1.3\bullet10^{7}$
MSP	kg Cu eq	$1.9\bullet10^{0}$	$4.1\bullet10^{2}$	$1.7\bullet10^{2}$	$4.0\bullet10^{3}$	$4.6\bullet10^{3}$
FSP	kg oil eq	$2.6\bullet10^{2}$	$1.2\bullet10^{4}$	$5.5\bullet10^{3}$	$9.1\bullet10^{4}$	$1.1\bullet10^{5}$
WCP	m^3	$8.4\bullet10^{0}$	$4.8\bullet10^{3}$	$1.3\bullet10^{3}$	$3.5\bullet10^{4}$	$4.2\bullet10^{4}$

In order to understand the contribution of each final product category in absolute terms and identify the impact categories which are more affected within the investigated system, the normalised impacts related to the production of 1 kg of each category product were also calculated (Fig. 4). Freshwater ecotoxicity (FETP) and marine ecotoxicity (METP) followed by human carcinogenic toxicity (HCTP) and human non-carcinogenic toxicity (HNTP) are the categories that are impacted the most. With reference to final product categories, NMX is leading followed by NCO.

The investigated environmental impacts also include the burdens generated by the disposal of the generated waste, pertaining to plastic and paper packaging. Impacts have been assessed according to the Greek national disposal mix provided by the Ecoinvent database, composed, for both types of waste, as 2% of open burning, 3% of unsanitary landfill, 95% of sanitary landfill and 1% of municipal incineration. Paper disposal represents more than 90% of impacts in almost all the impact categories, except for TETP (60%), FETP (50%), METP (49%) and HNTP (67%), as highlighted in Table 5. Analysis showed that the contribution of the packaging materials' disposal is not significant to the total, implying that the environmental hotspot of the examined production process is accredited to the type and the chemical composition of the raw materials used.

4. Discussion

4.1. Environmental impacts of food additives production

The obtained results highlighted how the direct impacts related to the investigated process are essentially negligible when compared to agricultural and chemical processes to produce the various components. Even though the lack of studies about the environmental impacts related to the production of food additives, these results seem to be in accordance with literature about food production and food supply chains, suggesting that the largest contributions to environmental impacts come from agro-industrial processes, thus identified as principal intervention hot spots for the improvement of the supply chain, together with the use of food packaging (Chen et al., 2021; Green et al., 2020; Krishnan et al., 2020). Looking at the total annual impact from the investigated system, NMX and NCO show the greatest share of environmental burdens which is accredited to the higher annual production of the two categories. The same trend is observed also in the analysis of normalised results for the production of 1 kg of each final product category (Fig. 4). This could be due to the mass allocation procedures highlighted in Section 2.3 (products with the highest share of production are assigned a higher

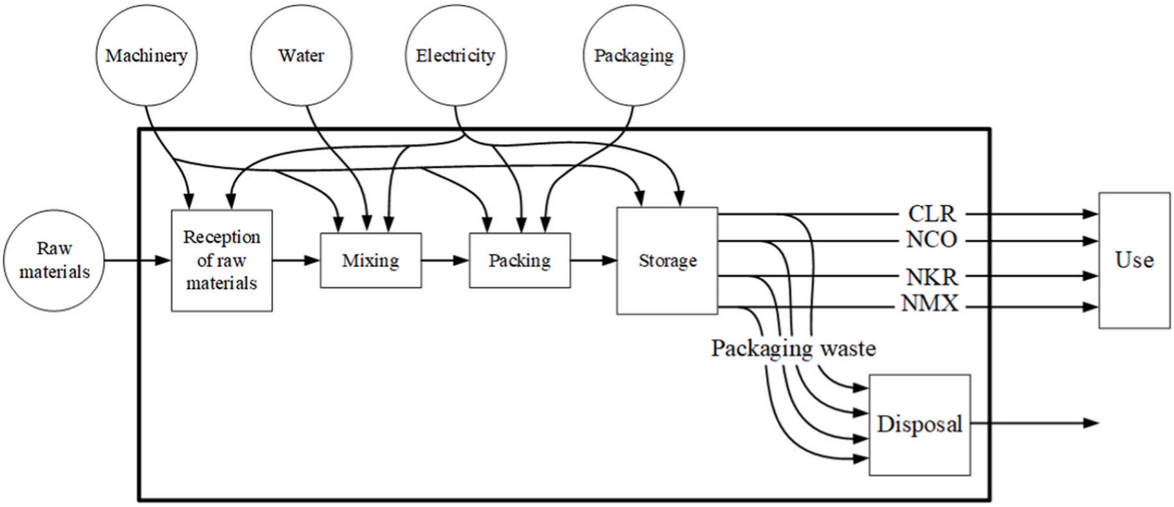

Fig. 2. Analogic model of the investigated case study highlighting inputs, productions steps, functional units, and system boundaries.

fraction of the impacts proportional to the fraction of output mass) and to the significant contributions from STR, AVO and CMC inputs, apparently characterized by higher environmental impacts.

Analysing more in depth the results obtained, the large shares of impacts falling within toxicity related categories are due to the partly agricultural and partly chemical nature of raw materials used. Agricultural based inputs are still supported by chemical products as fertilizers, pesticides and additives within animal feed. Chemical-industrial processes are also involved in the transformation of several agricultural products (e.g., glucose extraction from maize starch or phosphoric acid treatment for sodium phosphate production). Of course, energy generation is also responsible for the discharge of toxic substances in the various environmental compartments.

4.2. Implementation of circular economy practices

The results from the LCA showed that the environmental hotspots associated with the examined production process are connected to the raw material categories. The only exception is reflected in the CLR product category, where the highest contribution was related to plastic packaging. Nonetheless, the latter does not appear to be an unexpected outcome due to the nature of colourants that necessitate the use of plastic containers. Therefore, to evaluate the potential to mitigate the environmental impact related to raw materials, attention was placed on practices which aim at the reduction of raw materials and final product surpluses. For this purpose, as mentioned in the data collection section above, a series of face-to-face 30–45 min joint interviews with both the Quality Assurance and R&D Manager were arranged.

Owing to the long shelf life of raw materials and the ability to use the same in different final product mixes, recorded losses are extremely low, hence enabling the company to reach high levels of production efficiency while achieving a good level of stock rotation. Therefore, attention was placed on the management of surpluses that occur due to unforeseen factors, such as seasonal demand fluctuations, cancelled orders, or raw materials and final products that are close to their use-by or sell-by date. *"One of the key advantages of our production process is the long product life of the raw materials we use, as well as the fact that they can be used in more than one different final product category"*, commented the Purchasing Manager. The latter has allowed the company to extend their utilisation period, thus slowing down the flow of resources. Meetings revealed that the company has adopted a set of different reuse practices with respect to remanufacturing, repackaging, and redistribution. These take place both internal to the company, in the form of integration of raw materials in different product categories, as well as external, through collaboration with customers. As the Quality Assurance and R&D Manager noted: *"There are instances of having a product that is close to its expiration date, usually within* 2 months. *In this case, we retrieve it from our warehouse, we test its microbiological and chemical properties, we assess whether it is possible to extend its life duration, and depending on the results of these evaluation tests, we either extend its expiration date accordingly or re-use it to a new mix. Nonetheless, as a precautionary measure, every two months we conduct a random sampling of our products, and we send them for microbiological analysis"*. The timely and continuous stock monitoring, sampling, and grading process prior to two months from expiration, has facilitated not only the re-use and incorporation of the company's own products in alternative production lines, but also the minimisation of revenue losses through the ability to re-market them. When remarketing is not feasible, raw material surpluses are used for sampling purposes from the R&D department. With reference to final product returns, the steps involved in the redistribution process depend on the time interval since delivery and the condition of packaging. In detail, *"Each invoice includes a note clarifying that we accept returns within 30 days from the time of delivery, unless there is a problem with the product itself when this 30-day period restriction does not apply. The latter is quite common in cases of foreign matter contamination or any other problem with the mix. On the other hand, if they tell us that we do not need this product anymore due to changes in our production plans, as a company we have* 5-month *product-return flexibility subject to their storage conditions"*. Similarly, in the case of raw material inputs, returns that fall into these categories or returned due to mix issues or foreign matter contamination and are not expired or going to expire in the immediate future (less than three months), are graded, evaluated, and then sampled and sent for microbiological testing. Incorporation into new mixes, repackaging and redistribution in these cases occurs only if quality standards are met. Depending on the result of the evaluation process described above, the returned product is either forwarded to a different customer or discarded. However, the case of raw materials appears to be more complicated as the majority of suppliers are located abroad, *"When we receive raw materials unsuitable to use, we communicate with the respective supplier and we act according to the guidelines provided to us. However, when the quantity of returns is low, such as one or two sacks, or our supplier is located abroad, there is no value from a cost point of view to return it"*. Final products or raw materials that have expired or do not meet the quality standards past their expiration date or return, are sent to a local company for incineration. The latter approach constitutes a requirement as part of ISO9001 and ISO22000 standards that the company is currently certified to. According to the guidelines, the authorised state authority inspects the type and quantity of the non-compliant or expired product

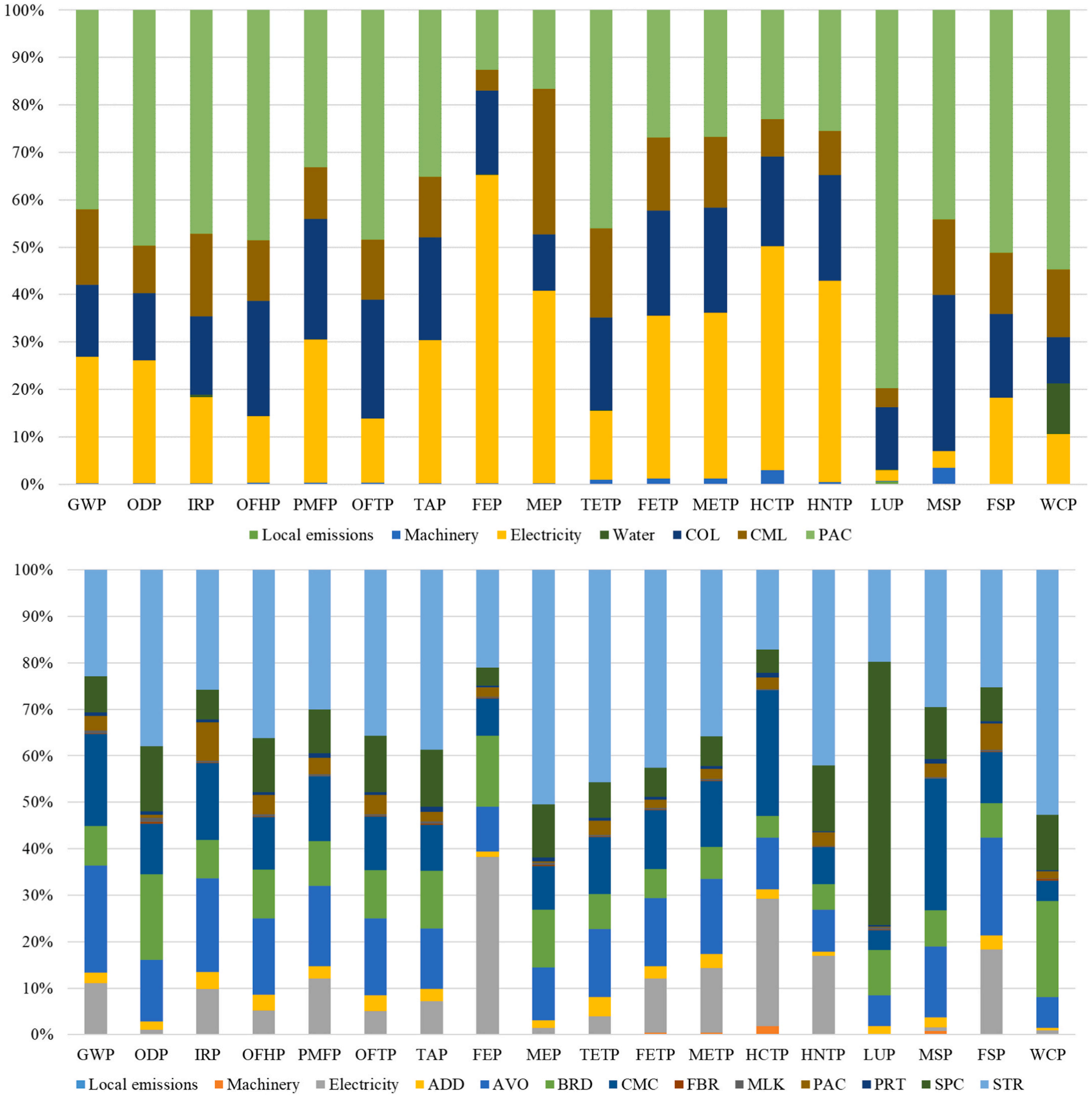

Fig. 3. a: Percentage contributions for the annual production of CLR. b: Percentage contributions for the annual production of NCO. c: Percentage contributions for the annual production of NKR. d: Percentage contributions for the annual production of NMX.

and issues the waste disposal protocol where it determines the disposal method, namely chemical neutralisation, incineration, or direction to landfill. A summary of implemented CE practices is provided on Fig. 5.

These findings are in alignment with previous studies in the context of the food processing stage that highlight the importance of different reuse options (e.g., remanufacturing and repackaging, redistribution, discounted and promotional sales) for the efficient management of surpluses (Garrone et al., 2014, 2016). However, what distinguishes this case study is that the examined company is a manufacturer of food additives and ingredients intended for meat processing companies, hence the same industrial sector, rather than final food products for the retail consumer market. Therefore, certain reuse practices, namely donations to food aid organisations (De Boeck et al., 2017; Richter and Bokelmann, 2016) and sales at a discounted price (Garrone et al., 2016) do not constitute an option for the management of processing surpluses as they have no use-value for the end consumer. Despite being a widely adopted waste management practice aiming at the minimisation of waste ending up in landfills, incineration (with or without energy recovery), is not considered to be a circular economy practice due to its entropic and polluting activity (Pires and Martinho, 2019). Alternately, preferred options for the end-of-life valorisation options for food processing waste and residues point towards the production of bioenergy and bio-based

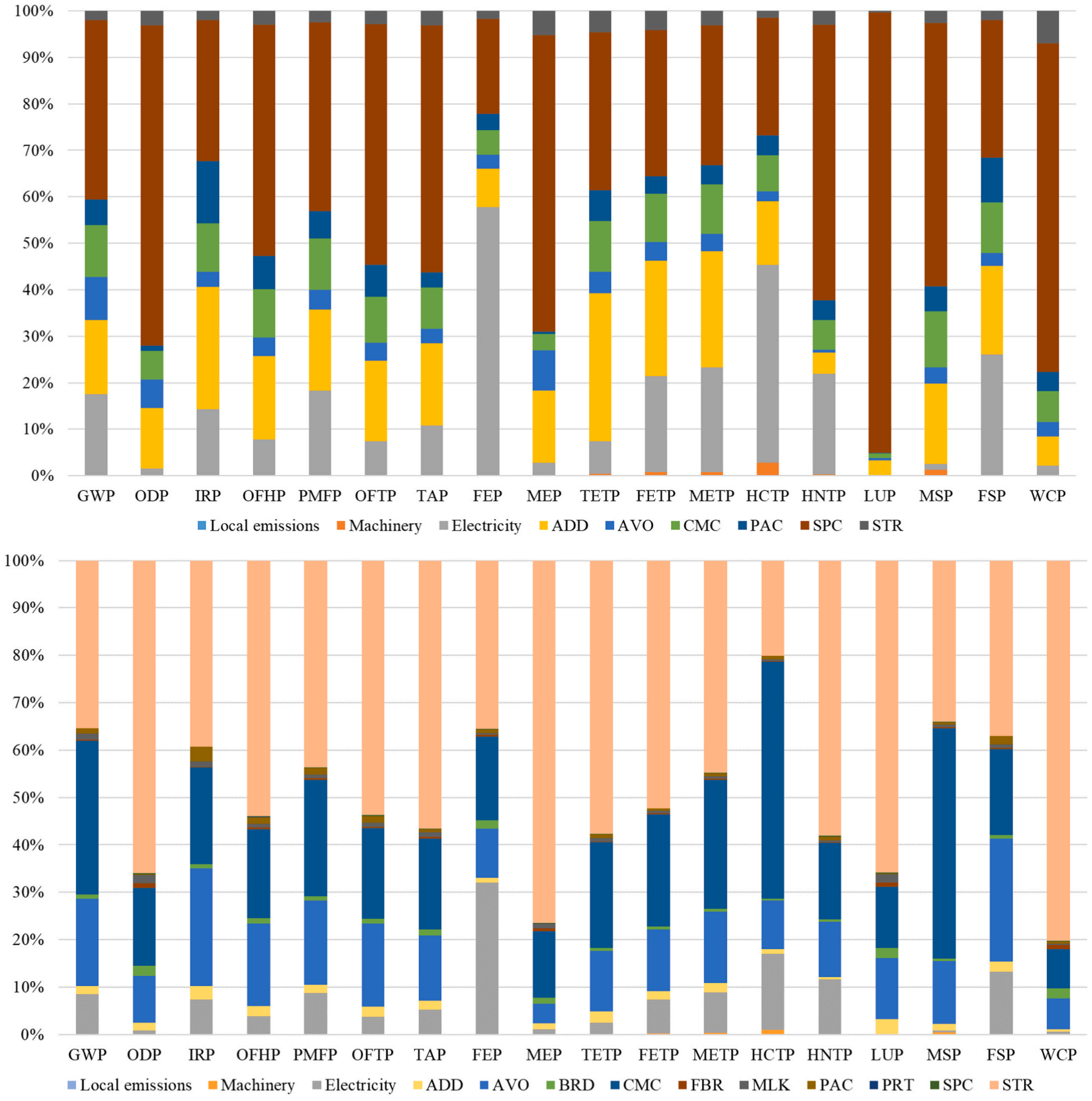

Fig. 3. (*continued*).

products, extraction of bio-compounds (e.g., polyphenols, pectin, lipids), as well as, when feasible, conversion into animal feed (Donner et al., 2021; Mirabella et al., 2014). Given the wide array and different types of the company's raw material inputs, such as spices, organic acids, carbohydrates, and proteins, the company should orientate towards different approaches for the treatment of surpluses intended for disposal. Owing to the high value of these bioactive compounds as an additive in pharmaceutical and nutraceutical industries, a preferable option from an environmental point of view would be their redirection and incorporation to these industries' manufacturing processes (Teigiserova et al., 2019). An alternative would be to consider in situ bioconversion of expired or excess food additives to improve the sustainability, though this would require a significant amount of investment where the benefits should outweigh the costs, or replace raw material ingredients with others of similar functions but with a lower environmental footprint (Pinelli et al., 2021; Molognoni et al., 2020). However, the identification of the most sustainable and suitable treatment option should also consider both the bio-chemical composition of inputs as well as other influencing factors (e.g., energy input, transport distance) to realise the desired net environmental savings (Scherhaufer et al., 2020) while maintaining the same product characteristics. At the same time, from a market perspective, since most of the suppliers are in foreign countries, the transportation of goods could share the logistics channels with other local enterprises. This would reduce costs and improve the economic benefits of the enterprise. In addition, biodegradable plastic packaging materials could be considered during the

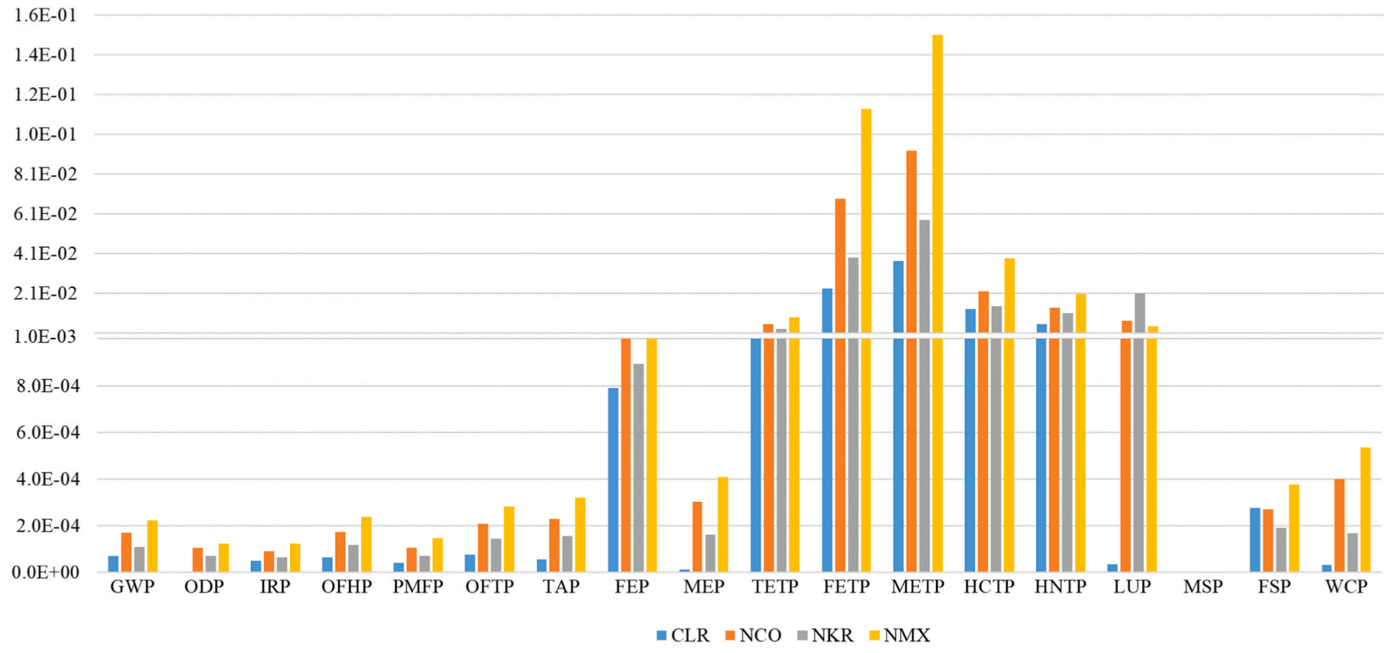

Fig. 4. Normalised ReCiPe Midpoint (H) results for the production of 1 kg of CLR, NCO, NKR, NMX.

Table 5
ReCiPe Midpoint (H) characterized results for packaging waste disposal.

Impact category	Unit	Total	Paper	Plastic
GWP	kg CO_2 eq	$1.0\bullet10^{4}$	99%	1%
ODP	kg CFC11 eq	$4.9\bullet10^{-4}$	97%	3%
IRP	kBq Co-60 eq	$8.4\bullet10^{0}$	97%	3%
OFHP	kg NO_x eq	$1.1\bullet10^{0}$	94%	6%
PMFP	kg PM2.5 eq	$8.0\bullet10^{-1}$	97%	3%
OFTP	kg NO_x eq	$1.1\bullet10^{0}$	94%	6%
TAP	kg SO_2 eq	$1.2\bullet10^{0}$	97%	3%
FEP	kg P eq	$3.6\bullet10^{-2}$	97%	3%
MEP	kg N eq	$3.6\bullet10^{0}$	94%	6%
TETP	kg 1,4-DCB	$8.0\bullet10^{2}$	60%	40%
FETP	kg 1,4-DCB	$2.0\bullet10^{2}$	50%	50%
METP	kg 1,4-DCB	$2.7\bullet10^{2}$	49%	51%
HCTP	kg 1,4-DCB	$1.7\bullet10^{1}$	93%	7%
HNTP	kg 1,4-DCB	$4.7\bullet10^{3}$	67%	33%
LUP	m^2a crop eq	$2.9\bullet10^{1}$	93%	7%
MSP	kg Cu eq	$3.3\bullet10^{-1}$	93%	7%
FSP	kg oil eq	$4.8\bullet10^{1}$	93%	7%
WCP	m^3	$1.9\bullet10^{0}$	93%	7%

repackaging process of the company's goods. By mitigating the generation of waste with greater environmental impact, it could reduce the cost of environmental treatment in the later stage. Finally, in the process of local redistribution of goods, renewable energy vehicles could be considered to replace traditional petrol vehicles. In general, planning from multiple dimensions is helpful to promote the realisation of a circular economy.

4.3. Causes of losses and waste

The adoption of different reuse practices concerning remanufacturing, repackaging, and redistribution has allowed the company to mitigate surpluses to the extent possible. While losses are low throughout the production process, discussions with top management highlighted waste as a seasonal issue, mainly associated with transportation during the summer season. As the top management noted, *"We have observed that there is a particular category of additives more susceptible to quality deterioration, specifically the ones that contain whey protein concentrates or nitrites. This is quite evident in the summer months when storage temperatures during transportation are well above the recommended ones. As a result of these conditions, such additives tend to petrify while nitrites become yellow, and packaging is oxidised"*. Having outsourced all logistical operations to third-party providers has exposed the company to limited control over storage conditions. The lack of controlled temperature storage during transportation along with storage temperatures that exceed the recommended ones result in the alteration of the shape of the product, causing mould and oxidation. Consequently, a considerable amount of delivered products are returned to the company and on most occasions, since they do not meet food safety standards, are directed for disposal. Pointing out the magnitude of the problem, the company's representatives commented: *"It's a prevalent issue because we have a series of products that when transported in storage temperatures well above the recommended ones, they are sweating and drying several times until they reach our final customer. Also, since our products are powders, transportation does not take place in fridge transportation"*. Due to the high perishable nature of food products, the time length of transport along with storage conditions (e.g., temperature, moisture, packaging) are important parameters not only in food quality and safety but also in the prolongment of their shelf life (HLPE, 2014). Extant research has mainly focused on the role of technological developments, particularly to Cyber-Physical Systems (CPS), Internet of Things (IOT), and Internet of Services (IOS) in the minimisation of food losses during transportation (Ciccullo et al., 2021; Defraeye et al., 2019; Gružauskas et al., 2019). On the other hand, little emphasis has been placed on the indirect effect of cost-driven strategic decisions, such as the outsourcing of logistics services, on increasing the risk of food losses and waste occurrence (Mena et al., 2011).

Raw material losses, although insignificant, were associated with surpluses that had exceeded their expiration dates. These were accredited to the limited capacity of used forecasting software to accurately predict seasonal fluctuations. Commenting on the issue: *"In terms of forecasting analytics, we are confined to the built-in function of our inventory management software. Nonetheless, our demand forecasts are based on our experience up until today. While there are no serious deviations from previous years' orders, still, in these past few years, we have experienced some extreme fluctuations in sales. For sure the recent pandemic has played a role in that but we believe that these fluctuations will tend to be the norm as years pass by"*. As Muriana (2017) points out, the market demand for food is subjected to both stationary and non-stationary phenomena that are affected by trends and seasonality. At the same time, food processors

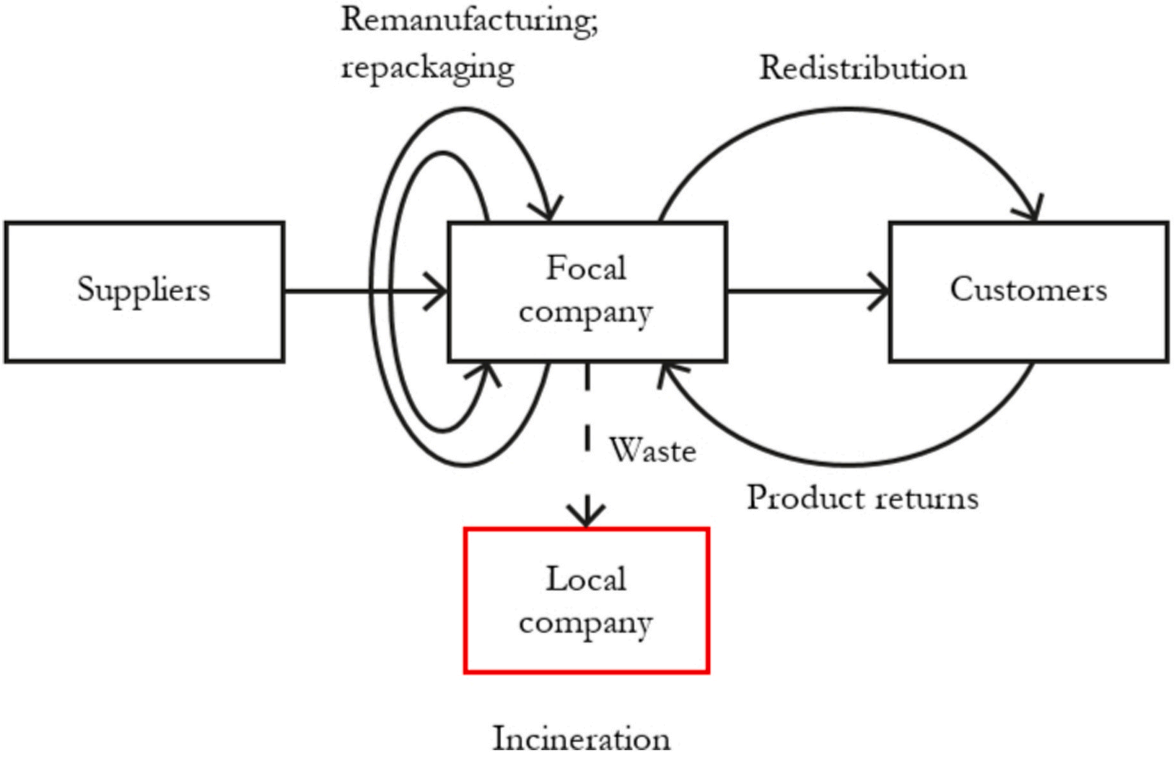

Fig. 5. Summary of implemented circular economy practices.

are tied to agreements tied to "retailer's service requirements" which obligate them to overstock products to prevent penalties. As a manufacturer of food additives intended for the meat industry, these requirements indirectly affect the operations of the examined company since purchasing decisions should create the capacity to meet the demand requirements of their customers. In addition, contrary to the vast base of customers located domestically, suppliers of raw materials are situated abroad making the return of raw material surpluses unfeasible from a cost point of view. Therefore, to align demand and supply, thus overcoming the occurrence of these surpluses, it is imperative to develop the capacity for collaborative demand forecasting through the adoption of appropriate tools (Gružauskas et al., 2019).

4.4. Social perspective

The LCA derived indicators presented in this work can be further processed to add some social insights to the performed environmental assessment in order to highlight the relation between social and environmental aspects (Willemsen, 2018) and to develop suggestions for policies and actions from different point of views (Ziman, 1998). As reported in Table 6, the results of social indicators and the comparison between the environmental performance of the investigated case study and the national production of food additives from a social perspective show that the Carbon footprint is comparable between the company and the national economy, while the national Environmental footprint is ~ 230 times bigger.

The socio-environmental indicators here calculated for the company participate in defining the value related to the national scale, being a part of it. The national level has been preferred to a multinational one (e.g., a European level) since the widest proportion of products is sold on a national market. Furthermore, food and food additives production are extremely variable among different countries and related to local customs and to internal regulations about food processing, conservation and allowed contents of additives. The comparison allows us to understand whether the investigated case study performs better or worse than the national average. The Carbon Footprint value is totally comparable, while the Environmental Footprint value seems to be performing largely better, but it must be taken into consideration that the national value includes all the activities which take part in the National economy. The CO_2 emissions per m^2 indicator combines information from the Carbon footprint and from the Environmental footprint, expressing the GHG (Green House Gases) emission per unit area, giving information about the performance related to the emissions of GHG in terms of the quantity of land which is necessary to sustain the economy. A small value can be related to small CO_2 eq. emissions or to a vast amount of land equivalent needed. Connecting the environmental and the social points of view through the use of proper existing and/or novel indicators might help future development in decision-making. Of course, different actions can be implemented to change the obtained values (e.g. outsourcing activities to suppliers), thus highlighting even more the need to adopt policy and social oriented perspectives through rigorous methods (e.g. social LCA, social impact assessment, surveys, etc.).

Table 6
Comparison between the socio-environmental performances of the investigated company and the national level.

Indicators	Unit per capita	Company	Greece
Carbon footprint	kg CO_2 eq	7.51	7.02
Environmental footprint	m^2a	176.17	41,000
CO_2 emitted per m^2	kg CO_2 eq/m^2	0.04	0.0002

4.5. Theoretical considerations

The central idea behind the environmental eminence of the circular economy is whether it can reduce the extraction of resources (Zink and Geyer, 2017). Circular business models (CBM) pertain to a framework that incorporates strategies aiming at slowing (reduce), narrowing (reuse), and closing (recycle) material and energy flows, ultimately leading to their reduction (Geissdoerfer et al., 2018). While closing these loops involves capturing the value of otherwise discarded materials, which is considered in a linear production and consumption model as post-use waste, slowing relates to product-life extension. Narrowing, on the other hand, refers to the reduction of resources used in the production process (Bocken et al., 2016). The adoption of different remanufacturing, repackaging, and redistribution practices through take-back agreements in collaboration with customers, has enabled the company to prevent losses and maximise the utilisation period of its raw materials and final products that would otherwise be discarded. However, it is evident that the inefficiencies caused by its limited forecasting capacity and inadequate transportation conditions offset the positive effect of implemented reuse practices. Therefore, it is imperative to develop the appropriate strategies and make the necessary interventions to facilitate collaborative demand forecasting and improve transportation to reduce surpluses and minimise waste. Current findings are aligned with previous observations that highlight the reductionist interpretation of CBM as revenue model configurations with limited attention to both upstream (Henry et al., 2020) and downstream innovations (Pieroni et al., 2019) that could potentially limit the generation of surpluses. It should be noted that the examined company belongs to this cluster of old businesses that have unconsciously adopted these reuse practices to minimise revenue losses rather than this late influx of circular start-ups. Therefore, to facilitate a true transition towards a circular economy it is of utmost importance, as depicted by Zink and Geyer (2017), to communicate the central idea of narrowing the loops and “displace” primary production. Having emerged as an “essentially contested concept” (Korhonen et al., 2018), it is imperative to consider countervailing discourses that will not retrofit circular economy in the dominant free-market context, thus altering its central purpose, but create the circumstances that could fit the paradigm (Genovese and Pansera, 2020).

5. Conclusion

LCA analysis showed that the environmental impact related to the investigated system is essentially negligible, characterized by minor local burdens, namely plastic packaging and raw material ingredient properties, specific to certain final product categories. Findings revealed that the occurrence of waste is not due to the absence of CE practices, but on the contrary, mainly due to secondary factors, namely poor transportation conditions and the limited capacity of forecasting software. The adopted set of different reuse practices (i.e., remanufacturing, repackaging, and redistribution) has reduced surpluses to the bare minimum, improving resource use efficiency while avoiding recurring costs. It is evident that to further minimise waste, the company should develop certain logistical and forecasting capacities which, from a market standpoint, given its size, potentially it would not constitute an economically rational choice. On the other hand, the exploration of alternate recycling options for the materials that would be otherwise discarded, especially with reference to the utilisation of bioactive compounds from other industries, depends on the scale that such secondary industries operate in the region as well their location.

From the social perspective, the indicators that have been used can provide a way to understand the contribution of the company to the national performances in terms of how much each consumer’s portion of production takes part to the emissions and land use. These elements draw a final picture of a good company performance, but also represent a suggestion for decision makers to take into consideration social aspects, beyond the environmental ones but connected to them, to evaluate companies’ behaviour. The Circular Economy concept advocated in this case study, while based on practices already implemented by the company, also draws from extant literature to highlight potential implications. The active practices influenced the quality and quantity of input and output flows included in the performed LCA assessment, while the other theoretical suggestions could concur in further improving the sustainability of the entire supply chain, even in hot spots often found outside the boundaries of the investigated system.

Taking into account these remarks, potential future research extensions could involve several different approaches to assess the environmental performance of the system by extending the analysis beyond the production process to different scenarios. These could include comparative studies between current state operations and potential solutions towards the mitigation of materials’ surpluses, such as the acquisition of a private temperature control logistics fleet. In addition, given the prospect of creating synergies with regional industries (e.g., cosmetic, nutraceutical) where certain categories of raw material surpluses could be redirected and utilised rather than discarded, in a ‘biorefinery’ perspective, these research proposals could also consider different routes which could optimally facilitate such collaborative networks. Nonetheless, such scenarios should also adopt an economic rationality perspective to assess whether such decisions could pose a threat to the sustainability of the company itself. Taking a more holistic view complementing environmental assessments with social and economy based indicators would allow a multi-dimensional assessment that could reveal the areas that attention should be placed to foster a transition towards a regional circular economy.

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Declaration of competing interest

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