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Evaluation of the environmental sustainability of agricultural production using the methodologies of emergy analysis and life cycle assessment. Case study, tomato grown in Mendoza (Argentina).

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Highlights

- The sustainability of tomato production is evaluated through LCA and EMA.
- Irrigation and fertilizers are the critical points.
- The local environmental dynamics are altered by the great dependence on external inputs.

Evaluation of the environmental sustainability of agricultural production using the methodologies of emergy analysis and life cycle assessment. Case study, tomato grown in Mendoza (Argentina).

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Abstract
This article evaluates the environmental performance of tomato production in Mendoza (Argentina) using two methodologies that share the same approach and part of the inventory: i) Life Cycle Analysis, a method that considers all flows (incoming and outgoing) involved in the life cycle of a product, and ii) Emergetic Analysis, which represents the environmental support provided directly and indirectly by the biosphere to economic processes in the form of resources and ecosystem services. The combined application of these two tools helps to identify critical points in the production system and to generate proposals for improvement and innovation. In this case, the critical points identified are irrigation and fertilizers. Specifically for the environmental category Climate change, crop irrigation represents 51% of the total impact, while seedling production represents 22%. The emergy analysis, without accounting for direct and indirect human labor, shows a low contribution of local natural resources to the final product (0.12%), as well as an environmental burden of 7.23%. The results show that the local environmental dynamics are altered because tomato production is mostly driven by external inputs, mainly fertilizers (especially nitrogenous fertilizers) and energy.

Keywords: life cycle approach; emergy; natural resources; horticultural production, sustainability.

Introduction
The food production sector is of paramount importance for the achievement of the United Nations Sustainable Development Goal "Zero Hunger" (SDG2). However, it is a major contributor to environmental problems of great concern, such as climate change, soil degradation, water consumption, energy use, etc. One of the challenges ahead is to decouple food production (which must grow to meet SDG2) from resource consumption and environmental degradation. This decoupling implies reducing the rate of resource use (energy, water, land, etc.) to obtain the same amount of food, thus reducing environmental impacts. One of the possible strategies to achieve this is to make use of more local renewable resources.

Food sector plays a leading role in Argentina's economic development through the generation of added value, tax revenues and foreign exchange. In international trade, products such as meat, soybeans, corn, wheat, peanuts, lemons, flour, vegetable oils, pears and wine, to name a few, stand out. The horticultural activity, on the other hand, is characterized by its great capacity to satisfy domestic demand. Vegetable production ranges between 8 and 10 million tons per year and is 65% represented by 9 species, with tomatoes in second place behind potatoes (MAGyP, 2020a).

The tomato (*Solanum lycopersicum*) is produced in almost all the productive regions of Argentina, which ensures the continuous supply of the domestic fresh market. The main producing regions are the provinces of Mendoza and San Juan (west-central region - Cuyo), the provinces of Salta and Jujuy (Northwest region of Argentina - NWA), the provinces of Corrientes and Formosa (Northeast region - NEA), and the provinces of Rio Negro and Buenos Aires. Tomato production averages 1,100,000 tons per year, of which 70% is for fresh consumption (MAGyP, 2020b).

There are three different tomato production systems in the country: field, semi-forced and greenhouse (MAGyP, 2020b). Field production is carried out without crop protection,or is managed with a guide, and is used mainly in Mendoza, Salta, Buenos Aires and Río Negro. The guide consists of fixing posts at the ends of the furrows in an east-west direction and joining them with wires covered with canes, leaves, etc., to protect the crop during the frost period. Occasionally, a trellis system is used to support the plant. Planting can be by seeding or by transplanting seedlings, and is done in early July, while harvesting is done in November. In the semiforced system, seedlings are planted in plastic tunnels to avoid the incidence of external factors that hinder growth and to obtain precocity. Once the plant emerges, the seedlings are transplanted to the field. Greenhouses require a covering that protects the crops, often with heating systems. Although this technology improves protection against frost and low temperatures, it favors the development of pests that must be controlled with phytosanitary products. In addition, the use of heating systems increases the consumption of exhaustible resources, the emission of pollutants and production costs. Three greenhouse production zones stand out: NWA, NEA, and Buenos Aires.

This paper evaluates the environmental performance of tomato production for fresh consumption in the province of Mendoza, considering a field system with seedling transplanting.

The assessment was carried out using methodologies developed under life cycle thinking. These tools are widely used to assess material and energy flows to and from a production process. They attempt to trace the use and fate of resources from extraction to final deposition (Ulgiati et al., 2010) and quantify the resulting impacts. In general, impact assessment methods can be classified into: a) those that focus on the amount of resources used per unit of product (upstream methods), providing valuable information regarding environmental support, and the hidden environmental costs of even those systems that appear to be "clean"; and b) those that focus on the consequences of system emissions (downstream methods), which are related to the immediate perceived impact on the local ecosystem and can show large differences between systems with similar "upstream" environmental performance (Ulgiati et al., 2006; 2010). The use of two or more methods that share a large part of the database and maintain their particularities enriches and strengthens the analysis, contributing to a more complete approach to system performance than if only one method were used.

This study uses both approaches: Life Cycle Analysis (LCA, downstream method) and Emergetic Analysis (EMA, upstream method), to consider the inputs and outputs of the system, as well as the environmental support required to obtain the product. LCA has been widely applied to food products, with the objective of identifying possible opportunities for improvement in environmental terms, evaluating alternative production practices and carrying out comparative evaluations (Cucurachi et al., 2019). Among these studies are mentioned: Meier et al., 2015; Poore and Nemecek 2018; Del Borghi et al., 2020; Majewski et al., 2020. On the other hand, EMA has been applied in studies of different processes and systems to assess, for example, resource use efficiency (Martin et al., 2006; Rótolo et al. 2015a), ecological integrity of ecosystem health (Campbell, 2000), tomato production at greenhouse in Sweden (Lagerber and Brown, 1999), production of tomatoes and other greenhouse vegetables in Iran combined with an analysis of farmers' social status

(Asgharipour et al., 2020), sustainability in fish farming systems (Gu et al., 2022), biogas production from a collection radius perspective (Sun et al., 2023), among others.

The combination of LCA and EMA has been previously addressed by some authors. Among them, Wang and Du (2023) evaluated the resources and carrying capacity of marine farming in China. Zheng et al. (2023) used emergy, carbon footprint and economic return to study the co-benefits of a system integrating agriculture and livestock. Rótolo et al. (2015b) investigated how land allocation and technological innovation affect the sustainability of agriculture in the Pampas region of Argentina, using a combination of material flow accounting, cumulative energy accounting, emergy analysis and the life cycle method.

Specifically for tomato production, several works are available that adopt one or the other methodology separately. As an example, the study by Nakhaei et al. (2022) focused on the evaluation of emergy indicators in greenhouse cultivation. On the other hand, Naseer et al. (2022) conducted an LCA study of different tomato production strategies in Norway; and Urbano et al. (2022) analyzed the environmental impacts in the life cycle of tomato production and transport to the final consumer, considering different farming systems and different supply models (traditional and zero-miles agriculture). Despite these advances, no studies have been found that combine both methodologies and are specific for tomato production.

1. Material and methods

2.1 Life cycle assessment

LCA is a tool widely used to evaluate the potential environmental impacts generated by products and services, considering their whole life cycle (extraction and acquisition of raw materials, production of matter and energy, manufacturing, use or consumption, end-of-life treatment, and final disposal).

An LCA study is structured in four phases (ISO, 2006a): i) definition of goal and scope, ii) inventory analysis, iii) impact assessment, and iv) interpretation. The goal should clearly state the intended application, the reasons for conducting the study and the intended audience. The scope of the study must ensure the achievement of the goal, which requires defining the functions of the system, the functional unit (FU), and the system boundaries, among other aspects. The FU provides a reference to which the inputs (energy, materials, etc.) and outputs (products, emissions, wastes, etc.) of the system are related. System boundaries define the processes to be included or excluded from the study, depending on the objective, data and cost constraints, assumptions made, etc. The inventory analysis phase comprises the data collection and calculation procedures necessary to quantify the inputs and outputs of material and energy in each process included, adopting the previously defined FU as a reference. The impact assessment phase involves associating inventory data with environmental impact categories and with specific indicators for those categories (such as global warming potential, land use, water use, human toxicity, among others). Additionally, the results of each indicator can be related to a reference value to obtain a single unit of measurement for all the impact categories evaluated (known as Normalization). It is also possible to assign priorities (relative importance) among the different impact categories (known as Weighting). Finally, the interpretation phase consists of identifying significant flows, processes, and impact categories according to the goal and scope of the study and drawing conclusions and recommendations to reduce these impacts.

2.2. Emergetic analysis

The concept of emergy was introduced by Odum (1988; 1996) as "the total amount of available energy (exergy) of a type (usually solar) that is required directly or indirectly to produce a given product or to support a given flow. Thus, the EMA considers the direct and free environmental provision, which is provided by sunlight, wind, rain, geothermal gradient, as well as the direct and indirect service provided by human labor, not only for the inputs contributing to the system under study, but also counting backwards in time to include the labor necessary to obtain the resources used for those inputs. All inputs are accounted for in terms of their solar emergy, measured in solar equivalent joules (sej) (Odum, 1996; Ulgiati et al., 2010; Brown et al., 2016). This retrospective accounting of energy analysis, to include the environmental work that was required to make a given resource available, is not considered in LCA. Notwithstanding these differences, LCA and EMA share much of the inventory.

The calculation of emergy fluxes, expressed in sej, can be done using equations 1 and 2, which cover mass, energy, or money fluxes and can be expressed per unit of time.

$U = \Sigma_i f_i * UEV_i$ (1)

$UEV_i = U_i/F_i$ (2)

Where,

U = total emergy used (sej),

f_i = different inflows to the system (as J, g, h y USD ó $),

UEV_i = Unit Emergy Value of i-th flows (sej/J; sej/g; sej/h; sej/currency), with UEV of solar radiation equal to 1 by definition. It is the emergy invested per product unit.

Flows (fi) are generally grouped into R (Renewables, such as solar radiation, rain and wind), NR (non-renewable or slowly renewable inputs, such as soil and groundwater), M (purchased inputs or materials, such as agrochemicals, fuel, electricity, etc.), L (direct labor, such as man-hours) and S (indirect labor paid with money, i.e. money paid for the labor involved in the manufacture and transportation of the purchased goods). These last two flows, in general, are referred to as L&S. All inputs are converted to emergy units according to equation 1, through appropriate UEVs (equation 2). These values have been established by different authors, who have studied specific flows, such as wind and geothermal energy (Liu, et al., 2021); groundwater (Buenfil, 2001), fossil fuels such as diesel oil (Brown et al., 2011), pesticides (Rótolo et al., 2015b), fertilizers (Odum, 1996). These inputs have been adjusted to the global emergy baseline (GEB, Global Emergy Base) of 12.00 E24 seJ/yr (Brown et al. 2016).

The groupings and relationships of flows allow different indicators to be obtained. In this work, the following have been selected:

%Ren = Renewability percentage, indicates the fraction of emergy used that is renewable,

$\%Ren = R/U*100$ (3)

EYR = Emergy Yield Ratio, indicates the advantage of local resources over imported ones,

$EYR = U/(M+L+S)$ (4)

ELR = Environmental Loading Ratio, indicates the pressure exerted by the activity on local environmental dynamics,

$ELR = (N+M+L+S)/R$ (5)

ESI = Emergy Sustainability Index, indicates the performance of the evaluated system

$ESI = EYR/ELR$ (6)

All these indicators can be calculated with or without accounting for flows associated with human labor (L&S). The spatial and temporal unit used in this work is the hectare and the year (unit/ha-yr).

2.3 Tomato production system

This article evaluates the environmental performance of tomatoes produced in the province of Mendoza, which is in central-western Argentina, at the foot of the Andes mountains. Specifically, the production site belongs to the Valle de Uco region, located in the central west of Mendoza.

The LCA was conducted considering the recommendations of the International Organization for Standardization standards (ISO, 2006a; 2006b). The FU was defined as “1 kg of tomato for fresh consumption produced and packed in the province of Mendoza (Argentina)”. The scope of the study is from the cradle to gate, so only the impacts of raw material supply, transportation, manufacturing, and packaging of fresh tomato are described, excluding downstream activities (Figure 1). The data correspond to averages of the 2016-2018 productive campaigns. The harvest yield considered is 105 t/ha and corresponds to a field production system. The activity starts with soil tillage after the previous harvest and ends with the packing of tomatoes in cardboard boxes. Land use (occupation), use of machinery for soil tillage, fertilization, pesticide application, irrigation, harvesting, and packing were considered. Direct and indirect on-farm emissions, seedling production and planting, manufacture and transport of fertilizers, pesticides and crates, fuel production and consumption, and electricity generation and distribution are included.

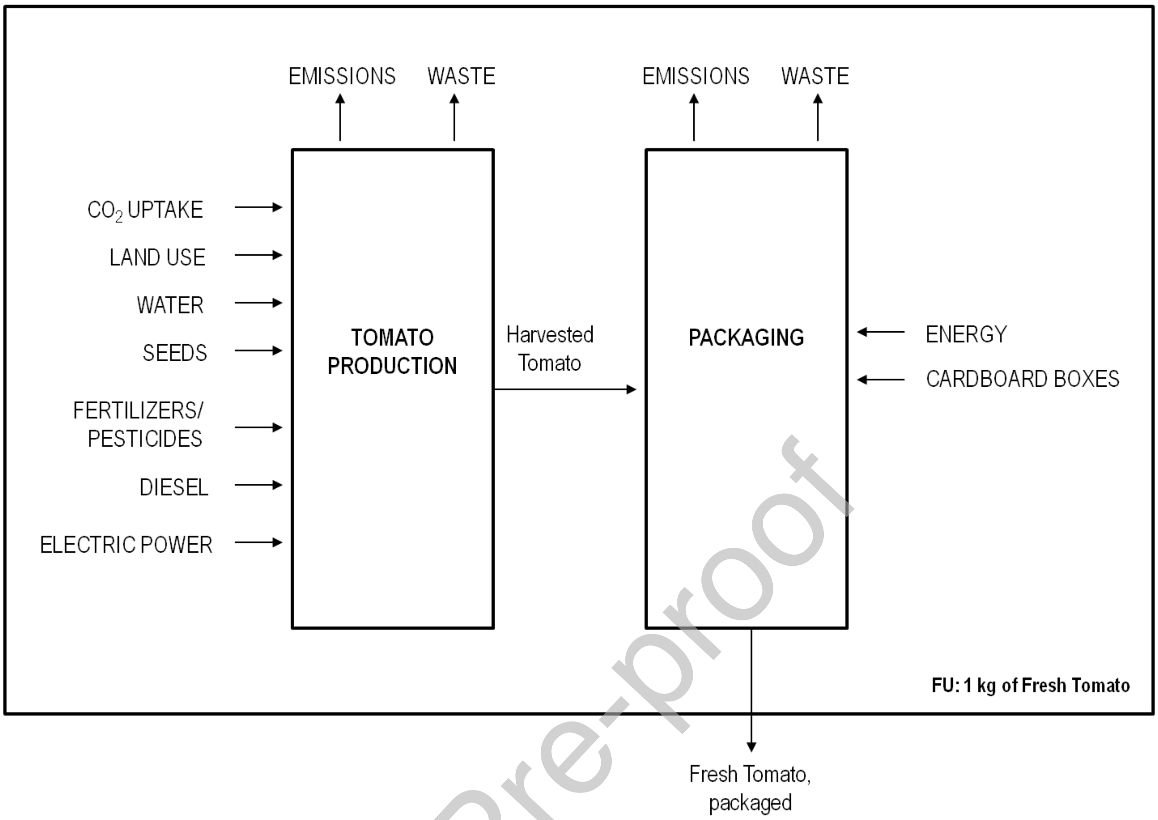

Figure 1. System boundaries for fresh tomato produced in Mendoza, Argentina

The life cycle inventory (Appendix 1) was elaborated with direct data provided by producers in the study area and complemented with literature (Polack and Mitidieri, 2005; MAGyP, 2020b; IDR, 2022; NEAD, 2015; IHFC, 2012). Some indirect data were extracted from the Ecoinvent 3.8 and Agri-Footprint 5.0 databases (e.g., agrochemical production, equipment manufacturing and transportation processes). Direct field emissions were calculated following the recommendations of Nemecek et al. (2019), including emissions to air, surface water, groundwater and soil. A soil occupancy time of 1 year was considered. As it is a single product system, no environmental load allocation considerations were performed.

The impact assessment was conducted using the CML Baseline model (World 2000), developed by the Center of Environmental Science of Leiden University (Guinée et al., 2001). This model is based on the problem-oriented approach and evaluates the environmental impact on various categories (Global warming, Human toxicity, Eutrophication, Acidification, Terrestrial ecotoxicity, among others), considered as midpoints between the environmental intervention (resource consumption and emissions) and the endpoint categories in the cause-effect chain. The results of the life cycle impact assessment are characterized and normalized (World 2000). System modeling and impact assessment were performed with the software SimaPro.

The EMA was conducted considering the scope defined for the LCA and the inventory data presented in Appendix 1. From this, the indicators described in section 2.2 (Equations 1-6) were calculated (see Appendix 2 for more details).

2. Results and Discussion

3.1 Life cycle impact assessment

The LCA results show that the most relevant impact category is Marine aquatic ecotoxicity, followed by Fresh water aquatic ecotoxicity (Table 1). The Human toxicity category ranks third in importance, while Eutrophication and Acidification impacts rank 4th and 5th, respectively. The Global warming category is in 7th place.

Table 1. Characterized and normalized LCA results to produce 1 kg of fresh tomato in Mendoza, Argentina

Impact category		Characterization		Normalization
Marine aquatic ecotoxicity	(MAE)	32.44E+00	kg 1,4-DB_{eq}	1.67E-13
Human toxicity	(HT)	1.60E-02	kg 1,4-DB_{eq}	6.30E-15
Abiotic depletion	(AD)	1.54E-07	kg Sb_{eq}	7.39E-16
Acidification	(Ac)	2.34E-04	kg SO_{2eq}	9.81E-16
Abiotic depletion (fossil fuels)	(ADff)	3.44E-01	MJ	9.05E-16
Fresh water aquatic ecotoxicity	(FWAE)	6.10E-02	kg 1,4-DB_{eq}	2.58E-14
Global warming (100a)	(GWP)	3.41E-02	kg CO_{2eq}	8.16E-16
Eutrophication	(Eu)	1.63E-04	kg PO_{4eq}	1.03E-15
Photochemical oxidation	(PO)	8.20E-06	kg C_2H_{4eq}	2.23E-16
Terrestrial ecotoxicity	(TE)	1.23E-04	kg 1,4-DB_{eq}	1.13E-16
Ozone layer depletion	(OD)	2.05E-09	kg CFC-11_{eq}	9.04E-18

Irrigation is the critical process for almost all the impact categories analyzed, except acidification, eutrophication and freshwater aquatic ecotoxicity, as shown in Figure 2. This is because the water requirement of the crop (543 mm/year) must be supplied almost entirely with irrigation water, given the low rainfall recorded at the study site. The irrigation system includes a groundwater extraction pump and a drip application pump, both of which require a significant amount of energy that has an impact on the evaluated impacts.

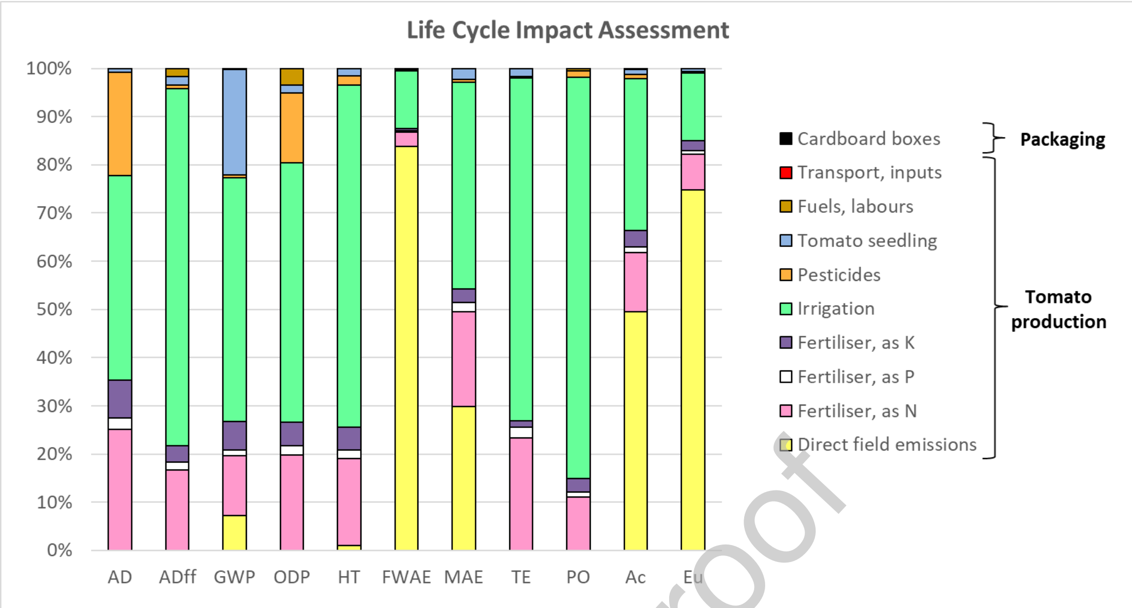

Figure 2. Process contribution to impact categories for tomato production in Mendoza, Argentina

Some measures that can be applied to achieve energy savings during irrigation are: selecting an adequate pipe diameter, avoiding pressure losses in the elements of the irrigation network (valves, elbows, sprinklers, etc.), and reduce the use of pressure reducing valves, since this implies that part of the network receives water with excessive pressure; size the pumping systems according to the water requirement (avoid oversizing); install variable speed drives, reducing the power absorbed by the pump during periods of lower flow demand and peak intensity at start-up; periodically perform maintenance to the installations and carry out periodic energy monitoring through the use of management indicators.

Soil emissions resulting from fertilizer application (direct and indirect emissions by leaching, volatilization, and runoff) are preponderant in acidification, eutrophication and freshwater aquatic ecotoxicity impact categories (Figure 2). These results agree with studies conducted for Italian tomato (Del Borghi et al., 2014; Manfredi and Vignali, 2014).

Fertilizer manufacturing, specifically nitrogenous fertilizers, also contributes greatly to the abiotic depletion and terrestrial ecotoxicity categories, accounting for 25% and 23% of the total impact, respectively (Figure 2). On the other hand, pesticide manufacturing stands out for contributing 22% to the total impact of abiotic resource depletion (Figure 2). The impacts resulting from the manufacture of fertilizers and pesticides, as well as the emissions arising from their application, can be reduced by implementing practices linked to Responsible Nutrient Management (RNM) and Integrated Pest Management (IPM). RNM involves adjusting fertilizer doses to crop requirements, phytosanitary status, and soil properties. This requires soil and foliar analyses to correct deficiencies or achieve adequate nutrient levels, ensuring a sufficient supply at the right time. An adequate RNM also contemplates the rotation of nutritional active principles, avoiding their excessive use. IPM involves the application of preventive, observational, intervention and control methods. The beginning of IPM is crop monitoring, followed by the determination of the control tactics to be used (crop management, climate, soil, legal regulations, interspecific relationships, and damage thresholds) and their effective use. This reduces the number of pesticides needed, the doses applied and, consequently, emissions to soil, water and air.

Finally, seedling production contributes 22% to the total GWP impact. However, in the other LCA categories the contribution is only from 1 % to 3 %, being these results close to those found by Manfredi and Vignali (2014) for Italian tomato.

3.2 Emergy sustainability assessment

Tomato production demands environmental services that cause a “load” on the environment. Once an environmental service is used by one process (food and water supply, nutrient cycling, disease control, among others), it cannot be used simultaneously by another process without seriously altering the local environment and ecosystems. In general, the environment has a renewability capacity to sustain the processes. However, this capacity is altered as the processes occur with greater frequency and greater intensity. Thus, there is a carrying capacity to economic development. This environmental work is measured by the Environmental Loading Ratio (ELR). The studied production requires direct environmental work as well as direct and indirect labor to obtain the product, which is reflected in the high value of the ELR, indicating the system pressure exerted on the local environmental services and therefore, on natural resources (ELR = 23.85) (Table 2). This value is about 220% higher than if the contribution of direct and indirect labor (L&S) were not considered, i.e. if only the environmental pressure exerted on the local system by purchased resources with respect to local resources were considered (Table 2, Figure 3 and Figure 4). This higher pressure is mainly due to local labor, which contributes 53% of the total emergy required by the system.

Table 2. Emergy flows and performance indicators of field tomato production in Mendoza, Argentina

Fresh tomato yields	**Values for 1 kg fresh tomato**
Mass Yield (kg)	1.00E+00
Energy Yield (J/ha)	8.00E+02
Economic Yield (USD)	6.50E-02
Emergy Flows (E+ 14 sej/unit)	**Values for 1 kg fresh tomato**
Local Renewable (R)	7.42E+09
Local No Renewable or slowly Renewable (NR)	3.01E+10
External inputs (M)	2.36E+10
Labor (L)	9.71E+10
Services (S)	2.63E+10
Total Emergy Used (without L&S), (U=R+NR+M)	6.11E+10
Total Emergy Used (with L&S), (U=R+NR+M+L+S)	1.84E+11
Performance Indicators (without L&S)	**Values for 1 kg fresh tomato**
EYR= (R + NR + M)/(M)	2.59E+00
ELR = (NR + M)/(R)	7.23E+00
ESI = (EYR/ELR)	0.36E+00

% REN (Renewability)=1/(1 + ELR)	0.12E+00
(a) UEV (sej/mass)	6.11E+10
(b) UEV (sej/energy)	7.64E+07
(c) UEV (E+12sej/economic value)	9.40E+08
Performance Indicators (with L&S)	**Values for 1 kg fresh tomato**
EYR=(R+NR+M+L+S)/(M+L+S)	1.26E+00
ELR= (NR +M+ L+S)/(R)	23.85E+00
ESI = (EYR/ELR)	0.05E+00
% REN (Renewability)=1/(1 + ELR)	0.04E+00
(a) UEV (sej/mass)	1.84E+11
(b) UEV (sej/energy used)	2.31E+08
(c) UEV (E+12sej/economic value)	2.84E+09

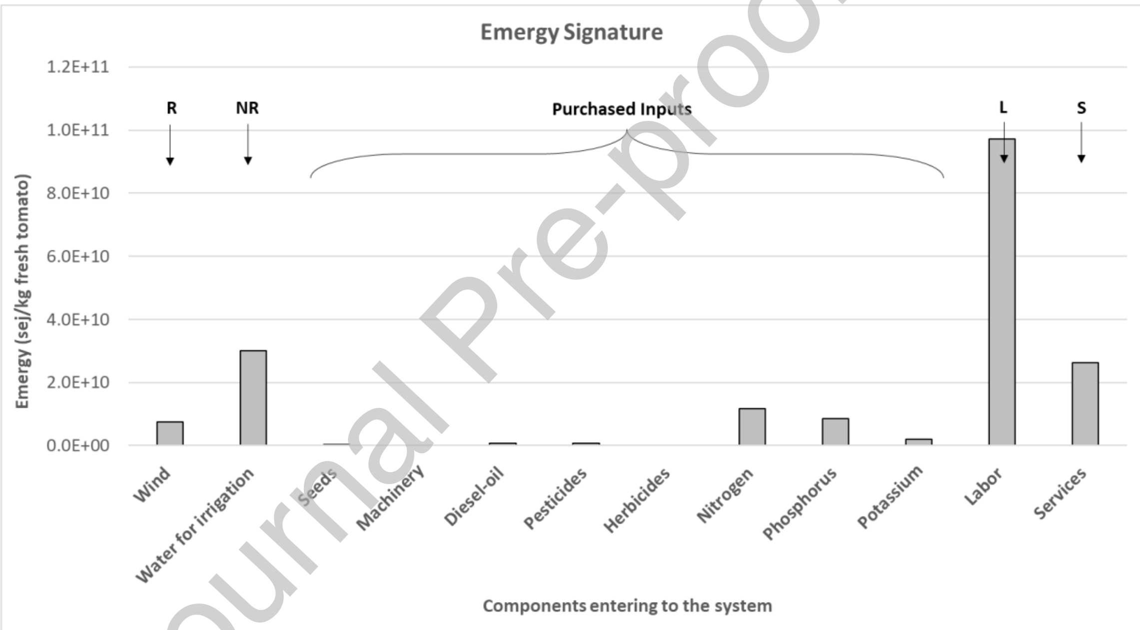

Figure 3: Emergy signature, including L&S, of fresh tomato production in Mendoza Argentina. It is a unique pattern. Each ecosystem has a set of environmental energy flows and storages that support its natural and economic processes. The emergy evaluation characterizes the resources of the areas and the contribution from the economy, which is distinctive for the analyzed process. This pattern is sometimes named "Emergy signature" (Odum, 1996).

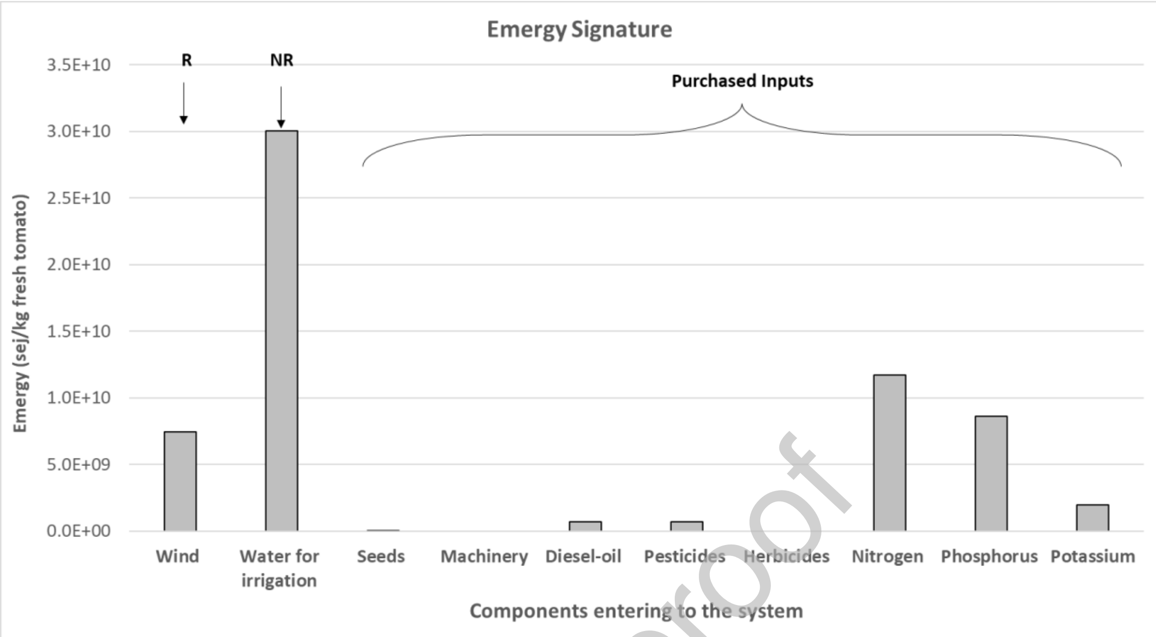

Figure 4: Emergy signature, without including L&S, of fresh tomato production in Mendoza Argentina. It is a unique pattern. Each ecosystem has a set of environmental energy flows and storages that support its natural and economic processes. The emergy evaluation characterizes the resources of the areas and the contribution from the economy, which is distinctive for the analyzed process. This pattern is sometimes named "Emergy signature" (Odum, 1996).

It is observed that, whether direct and indirect labor (L&S) are counted or not, the system's dependence on local renewable resources is low (% REN = 4% and 12% respectively). It is evident that it is a system with a very low sustainable environmental performance (ESI = 0.05 and 0.36 respectively) (Table 2). This system behavior is attributable to a high ELR where the contribution of groundwater (slowly renewable resource) for irrigation and the use of external inputs such as fertilizers are the most relevant of total emergy. When accounting ESI including L&S, groundwater, fertilizers, direct labor and services contribute 16%, 12%, 53% and 14% of total emergy, respectively (Table 2 and Figure 3). This "low emergetic sustainability" accounting for L&S is fundamentally given by the contribution of the employed labor that requires an environmental support to be able to exercise their skills. Therefore, from a regional point of view, the system depends on local labor that must always be available for these purposes, implying that it also has a positive impact on regional/local development. Lagerberg and Brown (1999) have analyzed tomato at field production in Florida (USA) utilizing data from the year 1995. They have demonstrated that direct labor contributes 13% of total emergy used. The difference with the present could rely on the spam time, where the ecosystems has been stressed for 24 years and therefore, more, and different work and external inputs are needed to obtain a good production. Another reason could lie in the need to update and homogenize the values of the emergy units used (due to the years elapsed between both studies) and to reflect the contexts and technologies used in both systems. Asgharipour et al. (2020) analyzed

greenhouse tomato production in Iran and showed that direct labor contributes 36% of the total emergy used. Due to the differences in management and production systems between the study by Asghariour et al and the present study, it is not possible to provide any explanation for the differences in the results of the emergy analysis.
When calculating the Emergy Sustainability Index without accounting for L&S (Table 2 and Figure 4), the resulting low value is mainly due to the contribution of groundwater to the system (49%) and secondarily due to the fertilizers used (36%). Among the inputs, nitrogen fertilizers (19%) and phosphorus fertilizers (14%) are the ones that contribute most to the total emergy required by the system. These values are indicating the depletion of water storages which recharges slowly, and the need of natural resources of producing external inputs that could be replaced by local inputs.
Figure 5 showed a diagram of the tomato system in energy language. There it can been seeing the renewable contributors entering from the left side of the picture), the inputs (entering from above) and the economy contribution from the right side. This disposition is for convention, as well as the symbols (circle are sources, tanks are storages, bullets are energy and mass interaction, diamond is money and mass interaction. See more details in Odum, 1996, page 5).

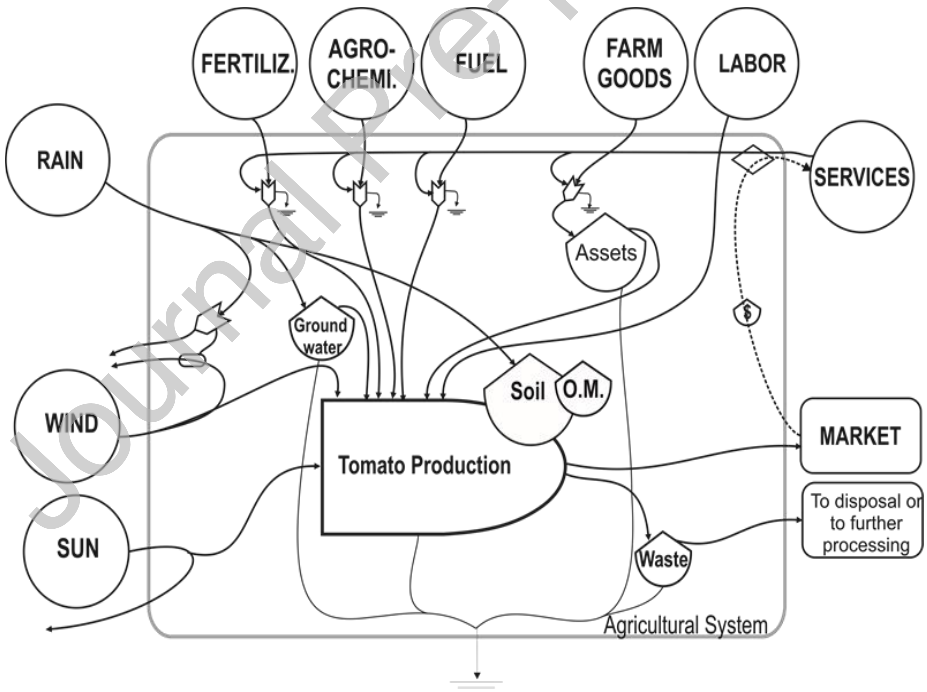

Figure 5: Energy systems diagram of fresh tomato production in Mendoza, Argentina. Adapted from Rótolo et al. (2014). Diagram symbols from Odum (1996).

3.3 LCA and EMA integration

The focus of this paper was to look for the complementarities of the LCA and EMA methodologies. In this order, it is emphasized that the LCA reports on potential impacts of the product studied on different environmental compartments (soil, air, and water), focusing mainly on emissions (Wang et al., 2020); while the EMA provides information regarding the environmental load exerted on the use of natural resources and the ecosystem services that support them. The EMA also allows to visualize the little dependence of the system under study on local renewable resources and the relevance of direct labor in this type of production. Both methodologies highlight that fertilizers and irrigation are critical points for the system studied. This can be seen from the point of view of LCA through environmental impact, and from the point of view of EMA showing the depletion of resources leading to an imbalance in ecosystem services (Boelee et al., 2011, Ulgiati et al. al., 2011).

The integration of these two points of view makes it possible to develop recommendations for improvement that go beyond those that could be defined by considering the two methodologies separately. For example, the relevance of irrigation, according to the LCA results, is mainly due to the energy required to pump the water, therefore, the recommendations are focused on achieving energy savings, as mentioned in section 3.1. On the other hand, the EMA analysis allows visualizing that the relevance of irrigation is associated with the groundwater dependence of the studied system (see section 3.2). Therefore, measures focused on energy saving will not be fully efficient to improve the results of the EMA analysis. A more efficient measure could be the use of ground covers to increase the soil's capacity to retain water and reduce evaporation losses. This would reduce the amount of irrigation water used, improving the value of the Emergy Sustainability Index and many of the life cycle indicators, such as Global warming, Abiotic depletion, Human toxicity and Terrestrial ecotoxicity. A similar example can be posed for fertilizers. According to the EMA results, one proposed improvement could be the use of biological inputs such as animal or poultry manure, to increase the contribution of local natural resources. However, this measure could increase the values for Terrestrial acidification or Ozone depletion since, for these categories, the potential impact of manure may be higher than that of synthetic fertilizers (Litskas, 2023). In this case, it would be more appropriate to evaluate the incorporation of RNM practices. It should be noted that the implementation of these practices can be difficult, given the resistance of local producers to adopt cultural changes (for example, making records of agrochemicals, performing periodic maintenance of equipment, measuring agrometeorological and edaphic variables, etc.), necessary to carry out the RNM. Likewise, a certain degree of lack of knowledge among producers about management techniques with an ecophysiological approach is highlighted, and about the economic benefits of improving irrigation equipment (they perceive the cost of the initial investment but not the economic benefits associated with water and energy savings). Several of these barriers coincide with those identified in the consultation workshop for primary sector actors, organized by CAME (Argentine Confederation of Medium Enterprises) (Iñiguez et al 2019).

Finally, it should be noted that although LCA and EMA address different aspects of the environmental impact of products and employ different assumptions and calculation procedures (Muazu et al., 2021), this work demonstrates that they can easily be used as complementary methods because they share most of the inventory data. This means that the implementation of the two methodologies to the same case study implies obtaining a broader picture of the environmental performance of the system addressed, with a minimum of extra investment in time and resources.

3. Conclusion

The sustainability of tomato production for fresh consumption in Mendoza, Argentina, was evaluated using the LCA and EMA methodologies. The LCA compiles input (inputs, raw materials, energy) and output (emissions, wastes, products) flows of the system and evaluates the associated potential environmental impacts. The EMA includes biophysical, economic, environmental and knowledge/information flows involved in the production processes, using solar energy as the unit of reference for the analysis it relates.

The results highlight the main hotspots of the system, and the potential actions that can be taken to improve its performance, such as to improve energy efficiency during irrigation, nutrient management and pest and disease management, which will reduce environmental impacts (LCA) and environmental load (EMA). It also makes it clear that this type of management is very vulnerable to external contingencies since it has a very low dependence on local renewable resources, while at the same time proving to be a beneficial activity for the region due to its direct labor requirement.

The results obtained show the complementarity achieved by evaluating the production system with two different tools, but both based on objective and quantifiable elements, which helps to show a broader picture of the impact caused. In this way, it was possible to include as much information as possible, use the same assumptions, limits, stages, flows, etc., and reduce the individual weaknesses of each methodology.

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of Competing Interest

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

Data availability

All inventory data generated and analyzed in this study are presented in this document. Data from the life cycle impact assessment and emergy analysis are presented in part and are available upon request.

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Appendix 1
Inventory data for 1 kg of fresh tomato produced in Mendoza, Argentina

Input Flow	**Amount**	**Unit**
Carbon dioxide, in air	1.01E-01	kg
Energy, gross calorific value, in biomass	9.04E-01	MJ
Occupation, arable irrigated	9.52E-06	ha year
Nitrogen fertilizer, as N (12-11-18)	2.00E-03	kg
Phosphorus fertilizer, as P (12-11-18)	3.81E-04	kg
Fertilizer, K (12-11-18)	8.81E-04	kg
Pesticide, Imidacloprid (seedling)	1.39E-06	kg
Pesticide, Formetanato	9.52E-04	g
Pesticide, Imidacloprid (transplant seedlings and post-transplant)	6.29E-06	kg
Pesticide, Copper oxychloride (post-transplant)	4.76E-03	g
Pesticide, Mancozeb	1.90E-03	g
Pesticide, S	2.86E-03	g
Pesticide, Captan	1.43E-03	g
Diesel	4.42E-03	MJ
Irrigation, drip	5.74E-02	m^3
Tomato seedling, for planting	1.88E-01	p*
Cardboard boxes	5.00E-02	p*
Output Flow	**Amount**	**Unit**
N_2O, air (direct field emissions)	3.77E-06	kg
N_2O, air (indirect field emissions, volatilization)	3.77E-07	kg
N_2O, air (indirect field emissions, leaching/runoff)	8.48E-07	kg
NH_3, air	7.02E-05	kg
NOx, air	7.18E-06	kg
Water, air	5.16E-02	m^3
NO_3^{-1}, groundwater	9.01E-04	kg
Cd, groundwater	3.57E-07	kg
Cu, groundwater	3.35E-05	kg
Zn, groundwater	1.27E-04	kg
Pb, groundwater	9.72E-07	kg
Cr, groundwater	1.82E-04	kg
Water, groundwater	1.14E-03	m^3
PO_4^{-3}, surface water	5.16E-06	kg
Water, surface water	4.59E-03	m^3
Imidacloprid (seedling)	1.39E-06	kg
Formetanato	9.52E-07	kg
Imidacloprid (transplant seedlings and post-transplant)	6.28E-06	kg
Copper oxychloride	4.76E-06	kg
Mancozeb	1.90E-06	kg

*Note: 1 p = 1 unit

Appendix 2
Emergy evaluation of fresh tomato produced in Mendoza, Argentina

Item/Operation	Row data (unit/kg)	UEV (sej/unit)	Emergy (sej/kg)
Local Renewable resources			
Sunlight energy (J)	3.34E+08	1.00 E+00	3.34E+08
Deep heat energy (J)	2.12E+02	4.90E+03	1.04E+06
Global Emergy sum			**3.35E+08**
Renewable resources			
Wind (J)	9.40E+06	7.90E+02	7.42E+09
Local Renewable Eemergy			**7.42E+09**
Non-Renewable resources			
Water for irrigation (J)	2.84E+05	1.06E+05	**3.01E+10**
Purchased inputs			
Perforated hose (kg)	0.00E+00	7.65E+12	0.00E+00
Polyethylene (kg)	0.00E+00	9.71E+12	0.00E+00
Seeds (kg)	3.81E-06	5.17E+11	1.97E+06
Machinery for different practices (kg)	0.00E+00	5.45E+12	0.00E+00
Diesel-oil (kg)	9.60E-05	7.26E+12	6.97E+08
Lubricant (kg)	0.00E+00	6.25E+12	0.00E+00
Electricity (J)	0.00E+00	2.21E+05	0.00E+00
Pesticides (kg)	1.96E-05	3.58E+13	7.02E+08
Herbicides (kg)	0.00E+00	2.47E+13	0.00E+00
Nitrogen, N (kg)	2.00E-03	5.84E+12	1.17E+10
Phosphorus, P (kg)	3.81E-04	2.26E+13	8.61E+09
Potassium, K (kg)	8.81E-04	2.21E+12	1.95E+09
Animal Manure (kg)	0.00E+00	8.48E+10	0.00E+00
Poultry Manure (kg)	0.00E+00	2.22E+12	0.00E+00
Green manure, organic (kg)	0.00E+00	1.32E+09	0.00E+00
Sum of imported materials			**2.36E+10**
Labor			
Labor for cultural practices and harvesting (h)	1.14E-02	8.49E+12	**9.71E+10**
Services			
Services in general-Tomato value			
Services in general-Tomato value (USD)	3.71E-03	7.08E+12	**2.63E+10**
Sum of inputs			**1.84E+11**
			6.11E+10
Output			
Yield (kg)	1.00E+00		

Yield (USD)	6.50E-02

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.