Pol. J. Environ. Stud. Vol. 25, No. 3 (2016), 1233-1243
DOI: 10.15244/pjoes/61757

Original Research

Ecological Footprints and CO_2 Emissions of Tomato Production in Slovenia

Denis Stajnko[1]*, Michael Narodoslawsky[2], Miran Lakota[1]

[1]Institute for Biosystem Engineering, Faculty of Agriculture and Life Sciences, University of Maribor, Pivola 10, SI-2311 Hoče, Slovenia
[2]Institute for Resource Efficient and Sustainable Systems, Technical University Graz, Inffeldgasse 21 B, A-8010 Graz, Austria

Received: 8 October 2015
Accepted: 10 February 2016

Abstract

The intensification of vegetable production has led to economic activities that profoundly influence the ecosystem. Measuring the environmental impact of these activities is important. Tomato (*Solanum lycopersicum* L.) production for fresh consumption grown under greenhouse, PE tunnel, and in open fields – as well as organic production – was used for estimating ecological footprint and CO_2 emissions. The reduction of food miles by introducing local production in Slovenia and the impact of alternative heating systems were considered, applying SPIonWeb software. The introduction of regional production (250 km) could reduce the ecological footprint of transport by up to 83.33% in comparison with transcontinental transport (1,500 km). Using alternative heating with geothermal energy might additionally reduce the impact of heating substantially. For the lower heating requirement of PE tunnel production, fossil fuels might be successfully replaced by pellets; thus, the footprint could be reduced by 61.88% in relation to fossil fuels.

Keywords: tomato, organic farming, ecological footprint, sustainable process index

Introduction

The growing demand for fresh, out-of-season agricultural produce has driven an increase in greenhouse-based production in Europe. However, greenhouse production is known as the most intensive method in agricultural production, owing to its high yield and high energy consumption per hectare [1]. As one of the most important greenhouse vegetable products, tomatoes can be grown practically the whole year in a greenhouse. Tomatoes belong to the category of warm-season vegetables that normally require higher temperatures and can also grow as a spring and summer crop in open fields.

Optimal conditions for plant growth requires daytime temperatures between 27ºC and 30ºC, and the root temperature should not be lower than 18ºC, because lower temperatures delay plant growth and fruit development [2]. The high temperature requirement of the tomato has caused uneven production across Europe; thus, transport to consumers is also an important part of the value chain. In 2010, annual tomato production for direct sale was about 7 Mt, among which Spain (2 Mt), Italy (1.1 Mt), and the Netherlands (0.7 Mt) were the main production countries [3].

Because of the large number of processes that contribute to production, heating, and transport, the assessment of the whole value chain environmental burden becomes

*e-mail: denis.stajnko@um.si

relevant to improving the energy and environmental performance of food products [4]. In order to transfer the production to more sustainable processes, it is essential that the entire life cycle with total burdening effects are considered [5]. However, according to difficulties in selection, a methodology that would be an effective tool for all types of production emerge [6]. In this context, the principles and framework [7] as well as methodology of life cycle assessment (LCA) [8] represents a sound methodological "backbone" for gathering data on and evaluation of environmental issues that may then be used to restructure the supply chain in order to improve its global environmental performance [9].

LCA is a method of evaluating the environmental effects associated with any given activity, beginning with the initial gathering of raw materials from the environment to the point at which all residuals are returned to the environment. Greater environmental awareness among consumers over the past decade has sharply increased the number of organizations conducting LCA studies [10]. One drawback of this approach is the limited comparability of the results, since they critically depend on the scope of the LCA, which may differ from study to study – even for the same products or services.

Since LCA's introduction in the 1990s several categories of environmental footprint have emerged, which are in close relationship with the worldwide concerns over threats to humans [11]. The most important category for evaluating agricultural processes is the ecological footprint [12]. It aimed originally at estimating the biologically productive area needed to produce materials and energy used by the population of a certain region (city, state, and world). The calculated area is compared to the area available to a certain population or individual, called the biocapacity. In cases where the ecological footprint is greater than the biocapacity, human consumption exceeds the natural carrying capacity [13]. It is based on an eco-inventory identifying all material exchanged with the environment throughout the whole life cycle. These flows are then evaluated with an appropriate ecological evaluation method. The result can be interpreted on area per unit of product basis (kg) or equivalent area (ha), where areas used outside the production unit are included [14].

The sustainable process index (SPI), developed by [15], is a member of the ecological footprint family; it is based on the concept of "strong sustainability," assuming that a sustainable economy builds only on solar radiation as natural input. Most natural processes are driven by this income, and the earth's surface acts as the key resource for the conversion of solar radiation into products and services. Global surface area is, however, a limited resource in a sustainable economy, and anthropogenic as well as natural processes compete for it. Therefore, the area required to embed a certain process sustainably into the ecosphere is a convenient measure for ecological sustainability; the more area a process needs to fulfil a service, the more it "costs" from an ecological sustainability point of view. This evaluation method has been customized for agriculture [16].

The main goal of our research was to compare the ecological impact of the various systems of tomato production most commonly used in Slovenia and to propose improvements to increase the sustainability of tomato production. Besides the footprint, CO_2 emissions potential will be presented for different production systems: organic, conventional field, conventional tunnel production, and hydroponic greenhouse-grown tomato. A particular focus was placed on organic production and its advantages in terms of the footprint, CO_2, and energy use.

Materials and Methods

Tomato (*Solanum lycopersicum* L.) production for fresh consumption was chosen for a case study because the tomato is an example of a plant with a high temperature demand, which can be grown in an open field in a mild winter climate, or even more under greenhouse conditions. Since the most important production areas are far from Slovenian markets, it affects regional as well as national-scale food supply chains and requires additional energy input for heating (greenhouses) and longer transport (open field).

Data

Data for this study was retrieved from interviews with tomato producers in eastern Slovenia in June 2013.

The annual mean air temperature of the area is 11.7ºC; the mean monthly minimum is in January at 0.4ºC, and the average monthly maximum is in July at 20.8ºC. Average annual rainfall in the area is around 800 mm [17].

The following production systems were compared in our research:

a) Greenhouse, glass covered, total area 10,000 m^2, production area 9,000 m^2 with additional heating;
b) PE tunnel, total area 10,000 m^2, production area 8,000 m^2 with additional heating;
c) Open field, integrated farming total area 10,000 m^2, production area 8,000 m^2;
d) Organic farming, total area 10,000 m^2, under a PE tunnel with additional heating; production area 8,000 m^2;
e) Organic farming, total area 10,000 m^2, under a PE tunnel without additional heating; production area 8,000 m^2.

In the greenhouse the tomato is hydroponically grown on coconut fibre wrapped in white PE 0.05 mm film. In all other systems, the plants are grown on natural soil, and basic soil cultivation was performed by ploughing and harrowing in the integrated as well as organic farming.

Grafted seedling propagation was identical for all five systems and lasts for 12 weeks in a greenhouse nursery. The rootstock was selected for its ability to resist infection by certain soil-borne pathogens, or its ability to increase vigour and fruit yield. The scion of the grafted tomato represents the upper portion of the plant and was selected for its fruit quality characteristics.

The following life cycle steps and system boundaries define the scope of the LCA:

a) Production and delivery of construction materials for the greenhouses and PE tunnels, and of the chemicals (fertilizers, manure and pesticides).
b) Production and delivery of energy sources (extra light oil, geothermal energy, pellets) and water.
c) The cultivation process, including the use of energy for additional heating and transport, water and materials during the various crop treatments and harvest.
d) Operational hours and maintenance of agricultural machines.

In our research, the system boundaries for ecological footprints are divided into three groups of processes, which will be discussed separately. The first one involves all processes needed for the production of fresh tomatoes without additional heating, and serves as a basis for evaluation of the other processes listed below.

The second group represents the footprint for transport of fresh tomatoes from the producer to buyers in Slovenia. Transport is not really dependent on the production system, but production systems usually have particular distribution and transport regimes linked to them. The high-tech greenhouse system was assumed to be located up to 1,500 km (Nederland) from the market and to produce tomatoes hydroponically year round, with the peak production from early spring to autumn. A 40-t truck is used for transport.

The PE tunnel greenhouse system is usually located in the Mediterranean region (Italy), which lies up to 500 km from the market and supplies tomatoes to Slovenia from April to November; thus, a 40-t truck is also used for transport. The local open field system is located up to 100 km from the market and supplies tomatoes from the end of May to the beginning of October. Daily production is smaller than in previous systems; thus, a 28-t truck is used for transport. Organic farming without heating supplies fresh tomatoes from local producers up to 50 km from the markets, and it is mainly seasonal and typically operates within the warmer months. The organic farming system with additional heating can supply markets located up to 50 km from farms for six weeks longer. The daily production of organic tomatoes can be transported by a 16-t truck.

In addition to these systems, the potential reduction of footprint in two alternative transport regimes from the greenhouses (250 km and 500 km instead of 1,500 km) and one PE tunnel (250 km instead of 500 km) will be considered.

The third group represents the use of typical heating systems (boilers using extra light oil - ELO) and comparison of its footprint with three alternative heating systems: geothermal energy in the greenhouse, wooden pellets in the PE tunnel, and organic production under the PE tunnel.

Heating System

Regardless of the production system, all PE covered tunnels are additionally heated with ELO using a 100 kW boiler for 4,000 m^2; warm air is distributed along the tunnel by a fan jet system that allows heat to be spread more evenly into the lower part. With proper maintenance, the lifespan of a boiler was assumed to be 15 years, and that of the PE jet tube system seven years. In our study the greenhouse is heated by geothermal water coming from a 1,500 m-deep well and a heat exchanger system. The lifespan of the geothermal well depends on the water flow quantity and is assumed to be 30 years.

In order to estimate the LCA impact of the heating system, two scenarios were foreseen: i) in the PE covered tunnel, the oil boiler (ELO) was replaced by a pellet heating system; ii) in the greenhouse, a comparison was made between a fossil-based heating system (ELO) and a geothermal energy with heat exchanger system; and iii) in organic production, ELO and pellet heating systems were compared.

Transport

Different scenarios were assumed for evaluating the transportation impact on the production of fresh tomatoes: local consumption with a maximum range of 50 km for the organic system, 100 km for the open integrated system, national markets with a 500 km transport range for PE tunnel production, and 1,500 km transport for greenhouse production. In both the latter production systems, regional 250 km transport was also assessed for comparison. Transport occurred by truck, with different loads depending on the quantity of daily production; thus, for organic production a 16-t truck, in open field a 28-t, and in the PE and greenhouse production systems a 40-t truck was assumed for analysis.

Infrastructure

On the basis of the interviews, it was assumed that the greenhouse structure has a lifespan of 20 years, while their foundations last 30 years. The tunnel structure lasts for 10 years, and its LDPE covers are replaced every seven years, while polypropylene ropes are used yearly to tie up the tomato plants. The lifespan of the irrigation pipes in high density polyethylene (HDPE) is three years in the open field and seven years in covered production. The soil protective white LDPE 0.05 mm (greenhouse) and black LDPE 0.05 mm is also replaced annually.

Production Systems

Table 1 lists the main operations for all production systems analysed in this paper. Each system is divided into four basic sub-systems: soil cultivation, weed management, pest (insects and diseases), management, and fertilizer application.

SPIonWeb tool

The ecological footprint of each production system was estimated by including environmental impacts related to fossil-C (kg CO_2/ha), air, water, soil, non-renewable, renewable, and area resources. Calculation of fossil-C assumed sedimentation of carbon to ocean beds, which requires about 500 m² of sea ground per year to put 1 kg of carbon back into the long-term (fossil) storage of the sea bed.

The footprint for emissions to water is based on a replenishment rate based on the precipitation rate in a specific geographic region of the compartment and a natural concentration of the emitted substance. In the SPI concept, the concentrations found in ground water are the reference for each natural compartment. The footprint of a given emission flow is therefore the area that is necessary to provide so much pure water via the seepage rate that may dilute emissions to the reference concentration of the emitted substance in groundwater.

The footprint for emissions to soil is similar to the footprint for emissions to water, and it is calculated based on the regeneration rate of the compartment soil calculated as compost generated from grassland and the natural concentrations of the emitted substances in the topsoil.

The footprint for emissions to air does not have a natural replenishment rate as do the other compartments, but the natural emissions of gaseous substances by forests are taken as a reference. The footprint for emissions to air is calculated as the area of forest that emits the same amount as the emission in question. CO_2 (kg) emissions are calculated from the "Area for fossil carbon," where the extracted fossil carbon and carbon-based materials are assumed to be oxidized to CO_2 over the life cycle and finally to end up as CO_2 emission to the atmosphere.

GWP potentials are calculated on the basis of GWP factors, where material flows of GWP are calculated by multiplying the GWP factor of the components. The sum of CO_2 life-cycle-emissions and other GWP-relevant impacts is the total GWP measured in kg CO_2 equivalent [16].

Results and Discussion

Input Processes in Different Production Systems

Table 2 presents all amounts of materials and machines used on 10,000 m² of total area in different production systems. The data were calculated per 1 kg of fresh tomato by using the information on annual yield (Table 2) and the facilities lifetime, which served as the basis for estimating the process impacts involved in the particular production. For installations and heating system, lifespan was described in detail in chapters 2.2 and 2.4.

Greenhouse production uses modern technology, which is fully automatized and thus requires considerable electricity, heating, water and chemical input. Electrical energy is mainly utilized by drives for opening/closing the roof, for pumps needed to run fertigation, and for the automation process itself.

Yields

Annual yields of tomato varied significantly among different production systems, i.e., from 495,000 kg/ha in greenhouse to 57,000 kg/ha in organic production (Table 2). The main reason lies in the energy and nutrition input, which in greenhouses enables the creation of optimal temperature conditions and thus an 11-month growing season and a nine-month harvesting season. The influence

Table 1. Tomato systems included in the study.

Production system	Soil cultivation and basic operations	Weed management	Pest management	Fertilizer application
Open field integrated farming according to the Slovene agriculture act and GAP*	Ploughing	Preventive use of herbicides	Preventive use of insecticides	NPK and N mineral
	Seedbed preparation planting	Plants growing on PE film Inter-row harrowing manually	Fungicides and fungicides according to GAP	Added by irrigation, based on soil analysis and nutrient removal
PE tunnel integrated farming according to the Slovene agriculture act and GAP	Ploughing seedbed preparation planting	Plants growing on PE film Inter-row harrowing manually	Preventive use of Pesticides according to the rules of INT** Management	NPK and N mineral Added by irrigation, based on soil analysis and nutrient removal
PE tunnel organic farming according to (EEC) No 834/2007	Ploughing seedbed preparation planting	Plants growing on PE film Inter-row harrowing manually	Use of organic preparations	1.4 LU*** of manure /ha
Glasshouse growing integrated farming according to the Slovene agriculture act and GAP	Hydroponic growing	Plants growing on coconut fibre bed, white PE wrapped	Use of natural predators	Soluble nutrients apply composted manure applied by irrigation

*GAP - good agricultural practice **INT integrated farming ***LU livestock units (650 kg dairy cow)

Table 2. Inputs and yields for different production systems of tomato (*Solanum lycopersicum* L. 'Buran F1').

Processes	Equipment and inputs	Production system				Units
		Glasshouse	PE tunnel integrated	PE Organic	Open-field integrated farming	
Ploughing	50 kW tractor	/	2	2	2	(h^{***})
Harrowing	50 kW tractor	/	1	1	1	(h^{**})
Basic fertilization (tractor)	50 kW tractor	/	1	/	1	(h^{*})
	NPK (7:20:30)	/	500	/	500	(kg/ha)
	Stable manure	/	/	24,000	/	(kg/ha)
Fertigation	N-fertilizer ($CaNO_3$)	11,000	500	/	500	(kg/ha)
	KNO_3	6,600				(kg/ha)
	KCl	630				(kg/ha)
	$MgSO_4$	4,600				(kg/ha)
	NPK (10:5:26)	/	1,800	/	1,800	(kg/ha)
	$MnSO_4$	40				(kg/ha)
	$CuSO_4$	5				(kg/ha)
Planting	50 KW tractor	/	1	1	1	(h *)
Pesticides	Confidor SL 200 (Insec)	/	5.2		/	(l/ha)
	Calypso SC480					(1/ha)
	Ridomil gold pepite (Fung) combi	1	1	/	/	(1/ha)
	Switch 62,5 WG (Insec)	0.12	0.12			(1/ha)
Water		22,270	10,500	5,400	4,800	(m^3/a/ha)
Electricity		19,800	1,080	340	340	(kWh/a/ha)
Heating		650,000	4,200	3,500	/	(kWh/a/ha)
Plants		11,500	60,000	60,000	80,000	(pieces/ha)
Yield		495,000	275,000	68,000	127,000	(kg/a/ha)

Intensity of machinery use: *light, **medium, ***high.

of higher cultivation temperatures is especially detectable when comparing open-field production to the same technology under PE, where open field production is just less than half that under PE. Heating, however, is not solely responsible for higher yields if the nutrition level is insufficient, as is evident in organic production under PE, in which higher temperatures increased the yield by only 1.1 kg/m^2, i.e., 19.2% in comparison to production without heating. These results correspond to the findings of [1], who reported the massive yield capacity of greenhouse tomato production and significantly lower yield for organic production.

Life-Cycle Impact Assessment (LCIA)

The ecological footprints of the assessed tomato production systems are presented in Table 3 as annual amount of biologically productive land necessary to assimilate the emissions produced in all pre-processes needed for production of 1 kg fresh tomato (m^2 a/kg). Generally, the largest footprints for production of 1 kg fresh tomatoes are related to production in a greenhouse (31.6018 m^2 a/kg), followed by open field integrated, PE tunnel, and organic under PE production (13.4639 m^2 a/kg). If the latter is supported by additional heating, however, a significant increase in the footprint (24.44 %) is detected. This rise may not only be attributed to energy, but is also caused by all other processes involved in the production of protective films, irrigation pipes, and mainly for the chemicals applied in all the management tasks given in detail in Table 2.

The largest quantity of CO_2 release during production of 1 kg fresh tomatoes is again related to greenhouse production (0.1180 kg), which is significantly higher than that

Table 3. Tomato footprint and CO_2 emissions under different production systems.

Production system	Footprint (m^2 a/kg)	CO_2 (kg)	GWP (kg CO_{2eq})
Glasshouse	31.6018	0.1180	0.2257
PE tunnel	18.2558	0.0681	0.4743
Open field integrated	19.4062	0.0673	0.1614
Organic under PE	13.4639	0.0419	0.0645

associated with the PE tunnel, open field, and organic production (0.0419 kg). It is important that the additional use of heating in organic production causes almost the same CO_2 emissions as conventional production in the PE tunnel system. This shows that the CO_2 burden is obviously mainly connected to the heating infrastructure and the type of energy applied.

The biggest GWP potential in the production of 1 kg fresh tomatoes is estimated in PE tunnel production and it is significantly higher than in the greenhouse and open integrated production (Table 2), owing to the application of PE-LD with a short life-span and the use of fertilisers and chemical protection. In contrast, the long life-span of glasshouse construction together with higher yields significantly decreased GWP. Contrary, both organic systems have significantly lower GWP, due to lower inputs of all materials and the use of natural predators, which prevents the development of some of the most aggressive insects without using pesticides.

Life-Cycle Impact Assessment (LCIA) with Transport

Although transport is not dependent on the production system, production systems are connected with particular distribution networks and the transport regimes linked to them, which are discussed in the following paragraphs.

Transport increases the ecological footprint and CO_2 emissions significantly in all production systems. The increase depends mostly on tons per kilometre (tkm) and the capacity of the trucks used for a particular destination and quantity of tomatoes. For this reason, transport of tomatoes from a greenhouse that is 1,500 km from the market leaves the largest footprint: 78.1644 m^2a/kg and CO_2 release (0.3219 kg) per one kilo of fresh tomatoes (Table 4). This exceeded the production itself by more than 200%. In contrast, the footprint for PE tunnel production was significantly lower (26.0548 m^2a/kg), owing to the lesser distance (500 km). In the case of open-field production with a transport distance of only 100 km, the footprint is additionally lower and lies at 7,110 m^2 a, which is only 25% of the production itself. The lowest footprint in both organic production systems (5.4442 m^2 a) is due to the shortest transport distances (50 km) and the use of smaller trucks. Although organic production can be found in the Mediterranean, a lengthy transport distance is against the organic producer and consumer philosophy, which requires fresh, locally produced food daily. As seen from Table 5, the transport footprint could be significantly reduced if production were closer to the markets (greenhouse 500 km, greenhouse 250 km, and PE tunnel 250 km). However, in those cases the heating scenarios change and increase the footprint, which will be discussed shortly.

Generally, the CO_2 released in transport affected the total CO_2 increase mostly in greenhouse production (0.3219 kg), which is again significantly higher than the figures for PE tunnel, open field, and organic production (0.0234 kg), and is highly dependent on the distances travelled as well as truck size.

The increase of GWP by transport is again the biggest (32.49%) whenever tomato is transported for 1,500 km. However, also the shorter transport (500 km from PE tunnel production) increased the GWP for 13.28% due to the use of a 28-t truck. On the other hand, the rise of the GWP is again the smallest within the local production and 50 km transport (organic system heated).

Heating in Tomato Production

The additional footprint and CO_2 release caused by conventional and alternative heating systems applied in greenhouse, PE tunnel, and organic production under PE

Table 4. Additional footprint caused by transport (km) of tomatoes produced by different production systems.

Production system (PS)	Footprint (m^2 a/kg)	Footprint (%)	CO_2 (kg)	CO_2 (%)	GWP (kgCO_{2eq})	GWP (%)
Glasshouse 1,500 km	78.1644	247.34	0.3219	272.79	0.073	32.49
Glasshouse 500 km	26.055	82.44	0.1073	90.93	0.025	11.07
Glasshouse 250 km	13.028	41.22	0.0537	45.51	0.014	6.38
PE tunnel 500 km	26.0548	142.72	0.1073	157.56	0.063	13.28
PE tunnel 250 km	13.028	71.36	0.0537	78.85	0.047	9.90
Open field integrated 100 km	7.110	36.63	0.0300	44.05	0.012	7.19
Organic under PE 50 km	5.4442	40.43	0.0234	55.84	0.006	9.30
Organic under PE, heated 50 km	5.4442	32.48	0.0234	33.96	0.006	5.96

Table 5. Additional footprint caused by heating in different tomato-growing production systems.

Production system	Footprint (m^2 a/kg)	Footprint (%)	CO_2 (kg)	CO_2 (%)	GWP ($kgCO_{2eq}$)	GWP (%)
Glasshouse-geothermal	0.377	1.19	0.0180	15.25	0.0250	11.07
Glasshouse- ELO	78.450	248.26	0.5255	345.00	0.7334	324.94
PE tunnel-ELO	1.749	9.58	0.0150	22.02	0.0144	3.03
PE tunnel-pellets	0.6667	3.36	0.0025	36.71	0.0063	1.31
Organic-ELO	5.5372	16.75	0.0340	49.34	0.0469	68.07
Organic-pellets	0.8602	4.88	0.0041	5.95	0.0078	11.32

are detailed in Table 5. In the first place, the location of the particular system is strongly connected with regional climate, as explained previously, which influences the net need for additional heating. On the other hand, heating impacts are strongly dependent on the energy input required by a particular growing system, as well the energy source used, whereby significantly lower values are calculated for renewable sources.

The biggest footprint is calculated when extra light oil (ELO) or gas is used for heating the greenhouse, because almost 0.125 l of ELO/kg fresh tomato is used in central European climate conditions for heating a greenhouse to 25ºC. For those regions, a geothermal heating system would be the best solution, since it leaves the smallest ecological footprint (0.377 m^2a/kg) for 1 kg of tomatoes, even though the 11-month greenhouse growing cycle consumes the most heat.

For all other heating systems that require lower energy input, the ecological impact is generally smaller, but again depends very much on the energy used as well the yield produced. Whenever geothermal energy is not available, heating with wood pellets would be the perfect solution, since it leaves a small ecological footprint in the PE tunnel (0.6667 m^2a/kg) and organic production (0.8602 m^2a/kg), respectively.

Heating with geothermal energy also causes lower CO_2 release than any other system, despite the high energy demand for drilling. But the long lifespan and huge yields reduce the CO_2 to 0.018 kg per kg fresh tomato. The largest CO_2 release (0.5255 kg) occurs in the case of heating a greenhouse by ELO, which is rarely done in practice, while all other systems show significantly lower releases. The small release (0.015 kg) for PE tunnel-ELO heating is due to the very short heating time, which is limited to the first weeks after planting. The use of pellet heating reduced the CO_2 release by 83.33% in PE tunnel and 87.91% in organic production. This fact makes renewable heating sources very attractive for use in organic production, thus becoming more sustainable.

The biggest effect of a heating system on the increase of GWP was estimated in greenhouse in the greenhouse production equipped with an ELO boiler (324.94 %), which might be explained by the pre-processing of ELO itself as well as the huge amount of ELO used over the growing season (Table 5). Also, ELO heating of organic production significantly increases GWP (68.07 %). The lowest additional GWP was estimated in PE tunnel production due to the very high yields. On the other hand, the introduction of renewable energy is in favour in greenhouse production (11.07 %) as well as in organic production.

SPI Footprint Breakdown for Different Production Systems

The following paragraphs offer deeper insight into the ecological impact for different production systems, using the categories; fossil-C, emissions to air, water soil, non-renewable resources, renewable resources, and land utilisation.

Regardless of the type of production system, the impact from the use of fossil carbon resources constitutes the

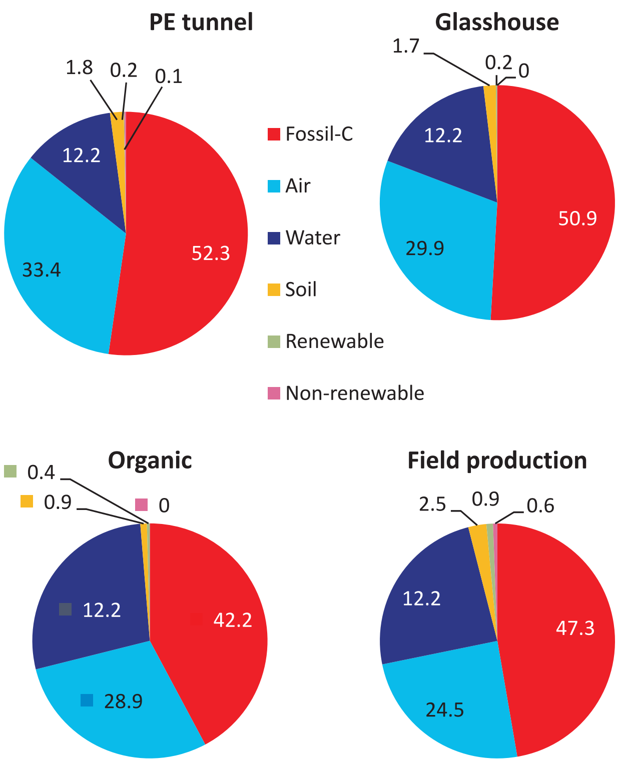

Fig. 1. The share (%) of SPI footprint categories for different production systems.

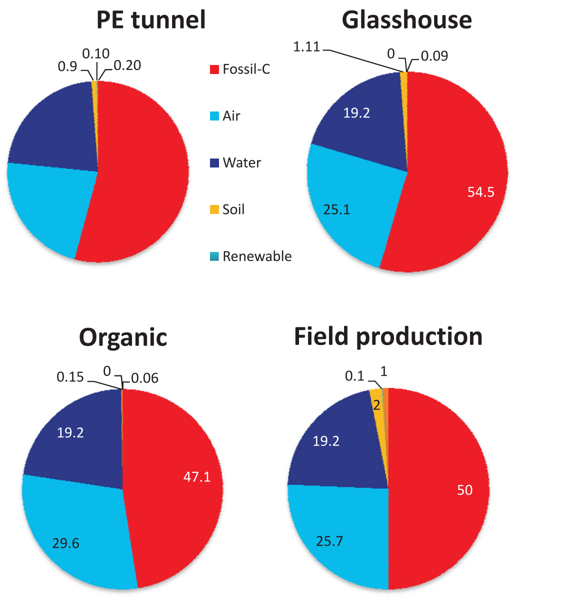

Fig. 2. SPI breakdown (%) for different production systems, including transport.

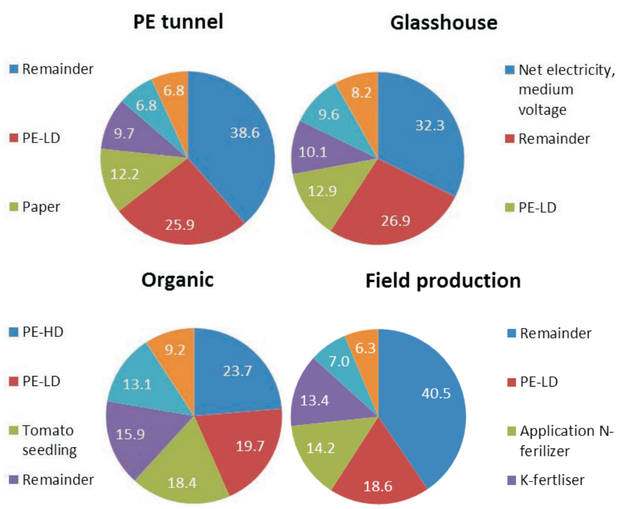

Fig. 3. SPI impact breakdown (%) for different production systems.

most important SPI category, ranging from 52.3% in the PE tunnel system to 42.2% in organic production. According to the SPI procedure, fossil carbon is the part of the life cycle oxidized to CO_2 and influences global carbon cycle emissions. The second most important SPI category for PE and greenhouse production involves emissions to water, in contrast to organic and field production, where emissions to air form the second most important source of ecological impact. The share of renewable resources (e.g., wood and grass) can be detected only in the field production system (0.7%), which means that in all other systems this particular source of impact does not exsist at detectable levels.

The influence of transport on SPI breakdown for different production systems and logistics (Fig. 2) shows the most important SPI impact categories for different tomato production systems, including transport. In all types of production system, fossil-C as the most important SPI category is becoming more prominent, and the maximal value of 54.5% was calculated for greenhouse production. However, differences in the breakdown vanish, as the contribution of fossil resource impact for the PE tunnel system (54.2 %) is not significantly lower. Transport strongly increased the fossil-resource impact in organic production, bringing it to 47.1%. The main reason for such a difference lies in the smaller ecological footprint of organic production itself, which was then influenced massively by transport.

Transport also has a significant impact on the air/water emission ratio, with a generally decreasing importance of emissions to water and an increase in emissions to air. The water part was most reduced in PE tunnel production, where it went down from 30.4 to 22.0%, while the air impact rose from 15.2 to 22.4%. On the other hand, the percentage of air emissions increased only from 28.9 to 29.6% in the organic system, and that for water deceased from 27.6 to 22.2%. The main reason lies in the combustion of diesel fuel, which is relatively smaller within the 50 km transport of organic tomato by an 18-t truck, but significantly higher for the PE tunnel system and the additional 500 km-long transport with a 40-t truck. In all other SPI categories, no significant changes were detected for any production system.

Life Cycle Breakdown for Different Production Systems

The following paragraphs provide detailed insight into the impact of different steps in the life cycle for particular production systems presented with the six most important processes responsible for the footprint.

Generally, the share of the most important inventory depends very much on the production system (Fig. 3). Since the share of the remainder is the percentage of processes in the pre-chain that are not detectable with SPI, our study will focus on the other shares. The most important life cycle impact in the PE tunnel system is PE-LD, which represents 25.9%, in the greenhouse electricity with 32.3%, in organic PE-HD with 23.7%, and in field production PE-LD with 18.5%. Electricity is the most important energy source for automated systems, and its share decreases from 32.3% in greenhouse to 9.7% in PE tunnel, while for other production systems it is not relevant. The reason lies in the smaller application of electrically driven equipment in organic and open field production. The situation is quite similar for the impact of plastic materials required for covering the tunnel, protecting the soil from weeds, and reducing water evaporation. The biggest share of PE-LD and PE-HD is in the PE tunnel, with 35.9 % impact; in the greenhouse 30.0%; 28.9% in organic; and 24.8% in open field. The third important group of impacts comprises the use of chemicals for weed and pest management as well as fertilizers. In the greenhouse, its share is only 9.6%, in PE tunnel 13.6%, and in open field 27.6%. In

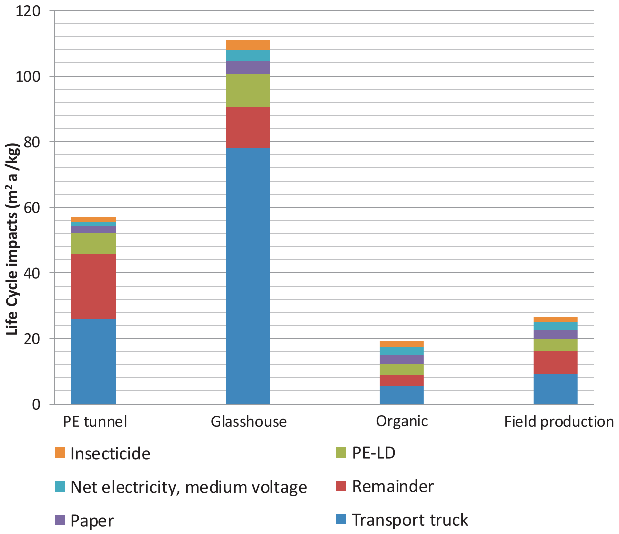

Fig. 4. Life cycle impact breakdown (m^2 a /kg) for different production systems, including transport.

organic production management there is no use for chemicals, which particularly increases the sustainability of this method of production. In contrast, a relatively high seedling inventory is calculated (18.5%), owing to the lower yield per plant, which is only half that in the open field.

Life Cycle Impact Breakdown for Different Production Systems, Including Transport

Fig. 4 presents the footprint inventories for production of one kilo of fresh tomatoes in particular production systems, including transport. Generally, the transport of tomato has a significant influence on the distribution of life cycle impact. In three of four systems, it represents the most important contribution to life cycle impact. The greatest impact (78.17 m^2a/kg) for the production of one kilo of fresh tomatoes was calculated for greenhouse production with transport by a 40-t truck to a 1,500-km distant market, 26.06 m^2a/kg for PE tunnel production, and 5.44 m^2 a/kg for organic production. In the case of field production, transport reaches 7.11 m^2 a/kg, which is the second largest share. One possible solution for reducing the huge transport impact share might be the introduction and encouragement of local (regional) production, which would use alternative energy sources instead of fossil energy. In that way, in the case of a 500 km-long transport by a 40-t truck, the impact would be only 26.06 m^2a/kg and 13.03 m^2a/kg in the case of 250 km-long transport. The use of a smaller 28-t truck for 100 km transport produces a lower impact (7.11 m^2a/kg), but it is useful only for local organic production. The transport impact might be significantly decreased by use of local, inexpensive energy resources (geothermal energy, wooden pellets), since it significantly reduces the production cost. In this way, locally produced tomatoes would become viable for purchase by chain-stores, which could also limit transcontinental transport during the winter.

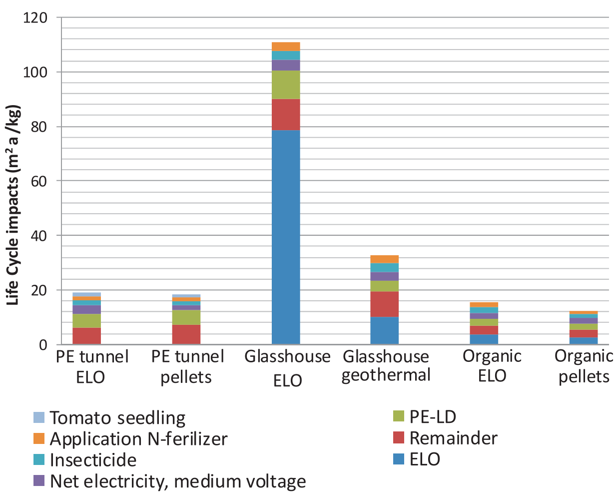

Fig. 5. Life cycle impact breakdown (m^2 a/kg) for different production systems, including heating.

Life Cycle Impact Breakdown for Different Production Systems, Including Heating

The following paragraphs will present the life cycle impact (m^2a/kg) of two different heating systems for each production system except open field production (Fig. 5).

As seen, the use of ELO heating increase the life cycle impact significantly in greenhouse and organic production systems, while in PE tunnel production, life cycle impact remains the same. In greenhouse production, the use of ELO heating creates the biggest impact (78.45 m^2a/kg) because it has the longest additional heating season; consequently, this method of heating exceeded all other impacts. In contrast, in organic farming the ELO impact is only 3.67 m^2a/kg; mainly due to the very short period of additional heating during the growing season. Again, in PE tunnel production the use of ELO heating is not detectable in the impact because it is used for only a few days during vegetation; besides, the yield is much higher than in the case of organic farming, so this impact is practically negligible. On the other hand, the use of alternative energy sources (geothermal energy or pellets) is not detected among the most important impact shares in any mode of production, since the pre-processes in those chains comprise very low impact.

Discussion

Several studies of LCA have been made in recent years concerning the environmental assessment of different methods of fresh tomato production around the world. The estimated ecological footprint caused by the transport of fresh tomatoes is not directly connected with the production itself. However, owing to the specific transcontinental connection between the production sources and markets, transport regimes are closely linked to these. For this reason, in our study, in the case of greenhouse and PE tunnel production, transport has the highest environmental impact (from 0.0936 to 0.9036 kg CO_{2eq}), but it is still lower than the figure from the Australian study conducted by [18], in which generally higher values (0.39 to 1.97 kg CO_{2eq}) were estimated, probably because of longer transport routes and the more efficient diesel engines in European trucks. On the other hand, [19] including only the transport of raw materials, which impact amounts from 0.023 to 1.04 kg CO_{2eq}, makes direct comparison in the area of transport impossible. Similar to our study, [20] also found a higher footprint in open-field than greenhouse production, thus greenhouse cultivation becomes a less harmful environmental option than open-field production if average tomato yields (Table 2) are considered.

Conclusions

Tomato is one of the most important European vegetables, which is marketed to consumers practically throughout the year. However, it belongs to the category of warm-season vegetables and requires higher temperatures for cultivation; thus, it is usually grown in a protected area in temperate climates. For this reason, the expected ecological footprint, CO_2 emissions, and GWP are generally higher than in open-field vegetables.

The results of the estimate of ecological footprint clearly indicated differences between various tomato production systems: greenhouse production leaves the highest ecological footprint at 31.6018 m^2a/kg, which is 55.86% higher than in PE tunnel production, 62.84% higher than in open-field production, and 134.71% higher than in organic production. Almost the same impacts were estimated also for CO_2 emissions (except for PE tunnel production).

Additional evaluation of the transport impact showed that long transcontinental transport is the most burdensome factor in fresh tomatoes from the greenhouse, amounting to 78.1644 m^2a/kg or (71.21%) of the total footprint. However, this could be significantly decreased if the transport is reduced to 500 km (-55.6%) or 250 km (-71.4%). The same pattern can be seen in the footprint for tomatoes growing under the PE tunnel, which are currently transported 500 km. This amounts to 26.0548 m^2a/kg, or 56.23% of the total footprint, but it could amount to only 13.028 m^2a/kg in the case of a 250 km transport distance.

Currently, the main reason for lengthy transport (from the Netherlands or Italy) is the favourable regional climate in southern Europe, which allows open-field and PE tunnel production from late spring to the end of autumn without additional heating, and greenhouse production with minimal ELO heating. However, the lower outdoor temperatures in central Europe can be offset to some extent by the application of alternative renewable energy sources, which together with a reduction in transport distances might significantly affect the ecological footprint and CO_2.

For instance, the replacement of fossil fuels by geothermal energy can reduce the footprint in greenhouse production to only 0.377 m^2a/kg (0.05 %), while the use of pellets is not beneficial for massive heat demands. However, in PE tunnel and organic production, heating with ELO can be successfully reduced (up to 87.06%) by introducing smaller pellet heating systems. In this way, locally produced biomass waste could be efficiently applied and thus help in reducing even the global ecological foot print, since long-distance ELO transport could then be reduced.

Acknowledgements

This article was created as a result of the applied project CRP V4-1062 etitled "Study of the impact of alternative tillage to improve soil fertility and increase the humus in the soil and reduce CO_2 emissions into the atmosphere," financed by the Slovenian Research Agency and the Ministry of Agriculture, Forestry, and Food of the Republic of Slovenia. The authors also acknowledge the vital contribution to Professor Michelle Gadpaille for her editing of the manuscript.

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