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Can the Carbon Dioxide Fixation of Processing Tomato Plants Compensate for the Emissions of the Tomato Industry?

Juan Ignacio Gutiérrez-Cabanillas [1,*], Elena Ordiales Rey [1], Micaela Carvajal [2] and Francisco Espinosa Borreguero [3]

[1] Centro Tecnológico Nacional Agroalimentario, CTAEX, Ctra. Villafranco a Balboa, km 1.2, 06195 Badajoz, Spain; eordiales@ctaex.com
[2] Group of Aquaporins, Department of Plant Nutrition, Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC), Campus Universitario de Espinardo, Apdo. de Correos 4195, 30080 Murcia, Spain; mcarvaja@cebas.csic.es
[3] Plant Biology, Ecology and Earth Sciences Department, Extremadura University, Av. Elvas s/n, 06071 Badajoz, Spain; espinosa@unex.es
* Correspondence: jgutierrez@ctaex.com

Abstract: Processing tomato is one of the most important crops in Extremadura region, Spain, since the largest national agricultural production and first industrial processing of this sector is concentrated in this area. In these two production stages, greenhouse gases (GHGs) are emitted, but there is also a capture of atmospheric carbon dioxide (CO_2) by the plants and therefore, this study focuses on assessing the carbon balance of this activity in this specific crop area. In this work, the amount of CO_2 fixed by tomato plants is evaluated, bearing in mind the production area and tomato cultivars. Subsequently, the carbon footprint is calculated, and finally, the carbon balance is established for each location. Under the conditions of this study, each processing tomato plant annually fixes 0.6090 kg of CO_2, and each kilogram of tomato produced allows 0.1905 kg of CO_2 to be captured. In contrast, GHG emissions average 0.0338 kg CO_2 equivalent; therefore, the carbon balance is clearly positive. Even adding the emissions from the industry to those from farming, the carbon balance of this activity is clearly positive (0.0900 kg CO_2 captured for each kg of tomato processed), indicating that processing tomato crops in this area of Spain could more than compensate for the emissions produced.

Keywords: carbon sequestration; carbon footprint; GHG emissions; carbon sink

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1. Introduction

One of the most important agri-food sectors in Mediterranean Europe is the processing of tomatoes [1]. In the 2023 season, 44.19 million tonnes (Mt) of processed tomatoes have been produced in the world. In terms of countries, the largest producer of processing tomatoes is the United States (11.92 Mt), followed by China (8.00 Mt), Italy (5.40 Mt) and Turkey (2.70 Mt). Spain is the fifth largest producer in the world of processing tomatoes, with 2.6 Mt in 2023. In Spain, the main tomato-processing region is Extremadura (70% of Spanish production) [2]. The main raw material for the tomato processing industry is the tomato fruit itself, produced in open-air fields and coming from specific cultivars that have the technological properties desired by the industry (colour, viscosity, firmness, etc.) [3]. Their agricultural production is associated with the emission of GHGs [4], but plants can also act as carbon sinks through photosynthesis [5].

The processing tomato sector has an environmental impact along the production chain, from the cultivation phase, the food processing, and the distribution phase to the end-of-life, as with all agro-industrial processes. In this activity, the field and transformation phases have the highest weight within some impact categories, such as Human Health, Ecotoxicity, or Climate Change [6]. In the specific case of the Climate Change Category, its impact has increased the vulnerability of the fruit and vegetable supply chain [7]. In this sense, the determination of the carbon footprint is an important indicator to assess the impacts of a

production system on global warming/climate change [8]. The carbon footprint may be defined as "the quantity of GHGs expressed in terms of CO_2 equivalent (CO_2-eq), emitted into the atmosphere by an individual, organization, process, product, or event from within a specified boundary" [9]. The set of GHGs and boundaries are defined in accordance with the methodology adopted. Different methodologies have been designed for their calculation, but the most widely used in public and private organizations are the Green House Gas Protocol (GHG Protocol) or the ISO 14.064-1 standard [10]. In addition, the United Nations Programme assesses the achievement of some of the SDG targets under this methodology [11,12]. According to ISO 14.064-1 standard, there are three scopes for carbon footprint calculation. Scope 1 refers to direct GHG emissions and removals, i.e., those from sources owned or controlled by the entity. Scope 2 includes indirect emissions and removals from electricity generation purchased and consumed by the entity, and Scope 3 includes emissions and removals from a company's value chain that are not under the control of the company.

On the other hand, agronomic ecosystems concurrently sequester, generate, and utilize carbon sources, potentially serving as either a net carbon source or sink at various temporal stages [13]. Through the primary mechanism of photosynthesis, plants function as carbon sequestration systems. In this process, plants assimilate CO_2, counterbalancing the loss of this gas via respiration and emissions from other natural processes, such as the degradation of plant tissues. In this way, the assimilation of CO_2 by photosynthetic organisms constitutes the only remobilization pathway from the atmosphere in the global carbon cycle. Globally, the biosphere binds an estimated 2 million tonnes of CO_2 annually, taking into account the release through respiration, organic matter decomposition, and other natural disturbances [14]. Consequently, CO_2 is converted into biomass, providing plant concentration of carbon between 45% and 50% of the dry weight. Nonetheless, studies have indicated that mature forestry might not offer a net benefit in terms of net carbon fixation [15]. Considering this, agriculture is emerging as one of the most effective sectors for mitigating rising atmospheric CO_2 levels.

The positive and negative effects of global change on agriculture have been widely studied [16,17]; in contrast, the effect of agriculture on climate change has only been reported in negative terms, with few studies on the net balance between gas emissions and fixation [18]. In many regions of the world, agriculture plays a crucial role in the economy of their countries, especially if all the indirect activities generated as a result of the farming industry are considered. Climate, combined with the general adoption of environmentally friendly agricultural practices, significantly increases the remunerative importance of this sector [19]. The inclusion of sustainable agronomic practices, such as not stripping the soil, reducing tillage, optimising fertilisation, and avoiding burning crop residues, would reduce the emission of millions of tonnes of GHGs [20]. Therefore, with a good farming practice code established, a positive balance could be possible [21].

Studies with tomato production only have been carried out taking into account the carbon footprint [22]. Furthermore, when industry emission was determined, the studies revealed that it doubled if peeled or diced and tripled if juiced [23]. The study of atmospheric carbon sequestration by agricultural crops is relatively extensive, and even more so is the study of GHG emissions from the agriculture and food industry. However, there is limited work assessing the overall carbon balance of a specific sector [24]. Therefore, the aim of this study is to evaluate if the carbon sink effect of processing tomato crops can compensate for the GHG emissions of this sector from both field production and first processing in the industry (mainly tomato paste and diced tomato). This work includes the quantification of the CO_2 fixed by the plants during their production cycle and the carbon footprint of the activity.

2. Materials and Methods

2.1. Plant Material, Site, and Condition

A field sampling was conducted in 10 processing tomato fields in the fertile lowlands of the Guadiana River (Vegas del Guadiana) in the region of Extremadura (Spain). In each location, different cultivars were grown, and each farmer carried out his usual Integrated Production management (Table 1). Plant sampling took place in the 2022 season.

Table 1. Location and characteristics of each field sampled of processing tomato.

Plot/Code [1]	Location	Area (ha)	Cultivars	Planting Date	Density (Plants ha^{-1})	Yield (Kg ha^{-1})
P1-LM	38°53′29.9″ N 6°38′19.1″ W	1.86	H-1015	18 May 2022	30,000	109,677
P2-LM	38°53′36.6″ N 6°40′24.3″ W	5.03	H-1015	12 May 2022	30,000	87,078
P3-LM	38°53′24.2″ N 6°39′41.3″ W	3.66	N 307	20 May 2022	29,000	101,366
P4-LM	38°53′07.0″ N 6°25′11.5″ W	1.98	Faber	16 May 2022	28,000	95,455
P5-UM	38°57′11.4″ N 5°57′09.8″ W	0.64	Encomienda	12 May 2022	26,000	98,438
P6-UM	38°57′02.0″ N 5°56′37.0″ W	2.92	Encomienda	12 May 2022	26,000	97,945
P7-UM	38°57′14.0″ N 6°09′27.0″ W	5.14	UG29814	04 May 2022	25,000	75,097
P8-UM	38°57′15.0″ N 6°09′39.9″ W	5.01	UG29814	04 May 2022	25,000	75,050
P9-UM	38°54′16.0″ N 6°05′02.4″ W	3.30	H-1534	16 May 2022	25,000	60,606
P10-UM	38°54′49.5″ N 5°58′39.9″ W	16.16	N 296	16 May 2022	28,000	96,186

[1] Code: LM represents the plots located in the "Vegas Bajas del Guadiana", and UM represents the plots located in the "Vegas Altas del Guadiana" within the region of Extremadura.

In this study, the processing tomato cultivars sampled were grown in several areas where this crop is significantly representative. Therefore, although growth and crop variables are different in other regions, this study shows the general pattern in this growing area.

2.2. Experimental Design

For the study, only the annual biomass production of all the processing tomato plants analysed was considered, both the aerial part (stem, leaves, and fruit) and the root, and they were harvested at the end of their crop cycle.

Ten plants from each plot were extracted from the soil with a hand shovel, taking care not to break the secondary roots, and then placed individually in breathable bags for processing. They were then separated into fruit, leaf, stem, and root and weighed to determine their fresh weight. Each plant fraction was dried to constant weight to work out the dry weight, and then, the dried sample was crushed and passed through a 1 mm screen.

Within the processing tomato supply chain, this work has focused on the cultivation phase, both on carbon sequestration by plants and on the emissions produced by cultivation, including harvesting. Therefore, emissions from the industrial stage of tomato processing in the same production area have also been taken into account based on previous data.

The following diagram shows the phases that have been carried out to meet the objective of this study (Figure 1).

2.3. Evaluated Parameters

2.3.1. Carbon Percentage, Carbon Content, and Carbon Sequestration in Plants

Carbon percentage (CP) was analysed in sub-samples (15–50 mg dry weight) of leaves, stems, fruits, and roots with an elemental microanalyzer LECO CHN-628, following the standard internal working procedure PNT01. The procedure is applicable to homogeneous, solid, non-volatile, and viscous liquid samples, which are combusted at 950 °C. Subsequently, the carbon content per plant (CC) was calculated using the dry biomass of each plant fraction.

$$CC = (CP_{root} \times DB_{root}) + (CP_{stem} \times DB_{stem}) + (CP_{leaves} \times DB_{leaves}) + \left(CP_{fruits} \times DB_{fruits}\right) \quad (1)$$

where CC is the carbon content of each plant fraction, CP is the percentage of carbon analysed in each plant fraction, and DB is the amount of dry biomass of each plant fraction.

The CO_2 calculation was also carried out using the same procedure as Lazzerini et al. [24].

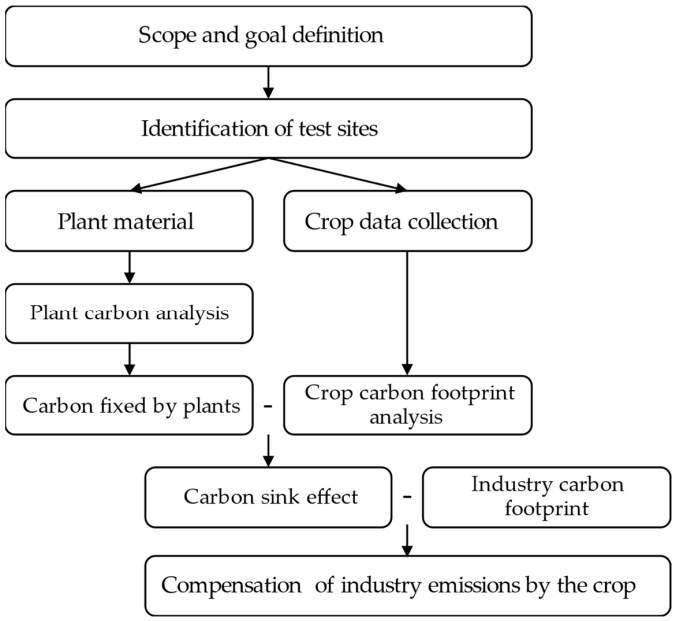


Figure 1. Schematic representation of the research stages.

2.3.2. Carbon Footprint of the Tomato Crop and Processing Industry

In this work, the UNE-ISO 14064-1 methodology was used to calculate the carbon footprint (CF) of the selected fields, using a specific calculator for agricultural crops developed by the Spanish Ministry of Ecological Transition [25]. This tool consists of a spreadsheet in which the emission factors for each component are updated annually. The access url provides calculation guidelines (https://www.miteco.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/calculadoras.html (accessed on 28 March 2024. The scope of this tool is 1 + 2 (direct emissions + indirect emissions due to electricity consumption). For this purpose, it was necessary to collect all the data shown in Supplementary Material (Table S1). Table S2 lists the fertilisers applied, and Tables S3 and S4 show the agricultural operations performed at each location.

The functional unit of calculation was 1 kg of fresh tomato produced, obtaining the CO_2 equivalent emissions (kg CO_2-eq kg^{-1}), which can be compared with the carbon fixed by plants when extrapolated to production terms.

These data were also added to the average emissions of the tomato processing industry in Extremadura from a previous work in which the same calculation methodology was used, described by Gutiérrez-Cabanillas et al. [1] (Supplementary Material, Table S5).

2.3.3. Carbon Balance

The carbon sink effect of the crop as compensation for the emissions of the industry (carbon balance) was obtained considering the functional unit (1 kg of fresh processing tomato), subtracting the result obtained in carbon sequestration (CO_2 fixed) from the result of the CF of both the crop and the industry.

$$Crop\ \mathrm{CB} = CO_2\ fixed - Crop\ \mathrm{CF} \quad (2)$$

$$Total\ \mathrm{CB} = CO_2\ fixed - (Crop\ \mathrm{CF} + Industry\ \mathrm{CF}) \quad (3)$$

2.4. Statistical Analysis

Data were analysed using the SPSS 24.0 statistical package (SPSS, IBM Statistics, Armonk, NY, USA). A descriptive analysis was performed in order to calculate the means

and standard error of the mean of the measurements obtained for each parameter. The GLM (General Linear Model) procedure was used to perform a one-way analysis of variance with the different locations and tomato varieties as the main effects. The level of statistical significance was defined as $p < 0.05$. In cases where the effect of some of the independent variables was significant, means were compared using Tukey's test ($p < 0.05$).

3. Results

3.1. Percentage of Carbon in Each Plant Fraction

The results obtained in the percentage of carbon are summarized in Table 2 According to the results obtained, on average, the highest CP in processing tomato plants is found in the fruit (38.86%), followed by the stem (34.76%), the leaves (29.13%), and finally the roots (27.84%). Depending on the crop location, different CP of fruits, stems, and leaves were found, being generally higher in the Vegas Altas del Guadiana area (UM plots) with the cultivars UG29814 and H-1534. On the other hand, there were no significant differences in the CP of roots.

Table 2. Percentage of carbon (CP) in each part of the plant by location.

Plot/Code [1]	CP of Root	CP of Stem	CP of Leaves	CP of Fruits
P1-LM	27.30	34.76 b–e	29.13 d	38.86 b
P2-LM	21.87	34.70 b–e	30.47 cd	39.65 ab
P3-LM	29.17	33.40 e	32.51 bc	39.50 ab
P4-LM	25.18	36.80 abc	31.04 cd	40.14 ab
P5-UM	24.61	34.49 cde	29.93 cd	38.78 b
P6-UM	33.01	34.13 cd	32.55 bc	38.73 b
P7-UM	29.83	36.25 a–d	34.45 ab	40.87 a
P8-UM	29.44	37.68 a	34.13 ab	39.94 ab
P9-UM	30.02	37.17 ab	34.05 ab	38.94 b
P10-UM	28.02	35.52 a–e	35.58 a	39.63 ab
Average	27.84	34.76	29.13	38.86
Significance (p)	ns	***	***	*

[1] Code: LM represents the plots located in the "Vegas Bajas del Guadiana", and UM represents the plots located in the "Vegas Altas del Guadiana" within the region of Extremadura. Different letters represent significant differences at $p < 0.05$. * and *** mean significance level $p < 0.05$ and significance level $p < 0.001$, respectively; ns means not significant.

The results obtained as a function of the cultivars grown were similar to those in Table 2. Thus, tomato variety influenced the CP of fruit, stem and leaves, but not of roots. Table 3 presents the CP in each part of the plant, considering the processing of tomato cultivars.

Table 3. Percentage of carbon (CP) in each part of the plant by processing tomato cultivars.

Plot/Code [1]	CP of Root	CP of Stem	CP of Leaves	CP of Fruits
N 307	29.17	33.40 c	32.51 bc	39.50 ab
ENCOMIENDA	28.81	34.31 bc	31.24 cd	38.76 b
FABER	25.18	36.80 a	31.04 cd	40.14 ab
H-1015	24.58	34.73 bc	29.80 d	39.25 ab
H-1534	30.02	37.17 a	34.05 ab	38.94 ab
N 296	28.02	35.52 ab	35.58 a	39.63 ab
UG29814	29.63	36.89 a	34.29 ab	40.41 a
Significance (p)	ns	***	***	**

[1] Code: LM represents the plots located in the "Vegas Bajas del Guadiana", and UM represents the plots located in the "Vegas Altas del Guadiana" within the region of Extremadura. Different letters represent significant differences at $p < 0.05$. ** and *** mean significance level $p < 0.01$ and significance level $p < 0.001$, respectively; ns means not significant.

3.2. CO_2 Fixed by Plants

3.2.1. CO_2 Fixed in Each Plant Fraction

Table 4 shows the amount of CO_2 accumulated in each plant fraction, depending on the location (kg CO_2 kg^{-1} dry weight of 1 plant). On average, each processing tomato plant accumulated 0.609 kg CO_2 per kg dry weight. The fraction with the highest amount of CO_2 fixation was the fruit (0.313 kg CO_2 kg^{-1} dry weight), followed by the stem (0.147 kg CO_2 kg^{-1} dry weight), the leaves (0.131 kg CO_2 kg^{-1} dry weight), and finally the roots (0.018 kg CO_2 kg^{-1} dry weight). There were no significant differences in the amount of CO_2 accumulated depending on the location of the plots (neither in the total nor in any of the plant fractions).

Table 4. CO_2 fixed of each plant fraction and total calculation (kg CO_2 kg^{-1} dry weight of 1 plant) by location.

Plot/Code [1]	CO_2 Root	CO_2 Stem	CO_2 Leaves	CO_2 Fruits	Total CO_2
P1-LM	0.013	0.113	0.117	0.295	0.539
P2-LM	0.018	0.165	0.121	0.397	0.700
P3-LM	0.017	0.130	0.118	0.236	0.501
P4-LM	0.025	0.160	0.136	0.266	0.588
P5-UM	0.015	0.167	0.147	0.325	0.654
P6-UM	0.017	0.089	0.111	0.328	0.545
P7-UM	0.015	0.164	0.148	0.439	0.765
P8-UM	0.017	0.126	0.131	0.350	0.625
P9-UM	0.024	0.198	0.154	0.274	0.650
P10-UM	0.016	0.161	0.124	0.224	0.525
Average	0.018	0.147	0.131	0.313	0.609
Significance (p)	ns	ns	ns	ns	ns

[1] Code: LM represents the plots located in the "Vegas Bajas del Guadiana", and UM represents the plots located in the "Vegas Altas del Guadiana" within the region of Extremadura. ns means not significant.

Table 5 shows the amount of CO_2 accumulated in each plant fraction, depending on the planting cultivars (kg CO_2 kg^{-1} dry weight of 1 plant). According to the results obtained, the cultivars studied had no influence on the amount of CO_2 accumulated in each of the plant fractions, nor was there any influence on the total biomass of the plant.

Table 5. CO_2 fixed of each plant fraction (kg CO_2 kg^{-1} dry weight of 1 plant) by processing tomato cultivars.

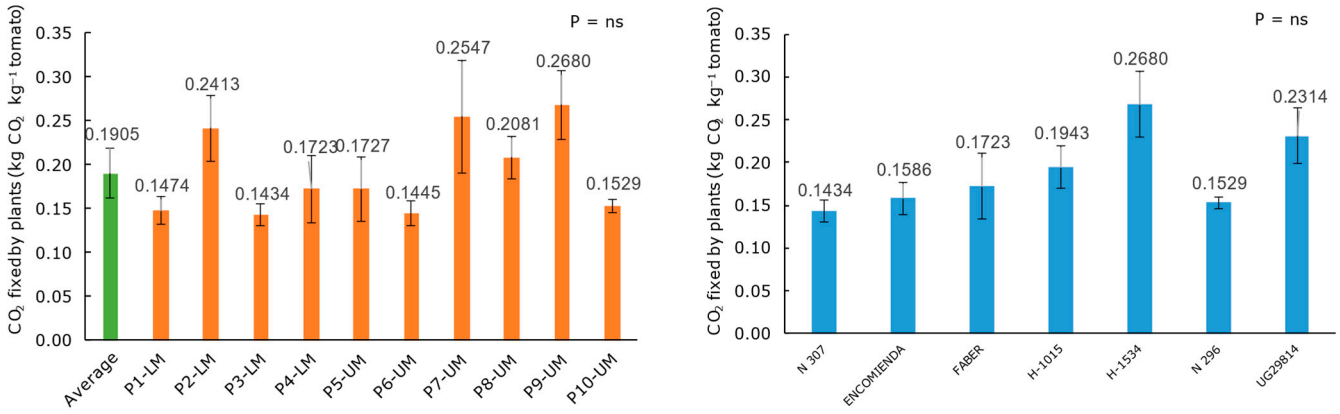
Plot/Code [1]	CO_2 Root	CO_2 Stem	CO_2 Leaves	CO_2 Fruits	Total CO_2
N 307	0.017	0.130	0.118	0.236	0.501
ENCOMIENDA	0.016	0.128	0.129	0.326	0.599
FABER	0.025	0.160	0.136	0.266	0.588
H-1015	0.015	0.139	0.119	0.346	0.620
H-1534	0.024	0.198	0.154	0.274	0.650
N 296	0.016	0.161	0.124	0.224	0.525
UG29814	0.016	0.145	0.140	0.394	0.695
Significance (p)	ns	ns	ns	ns	ns

[1] Code: LM represents the plots located in the "Vegas Bajas del Guadiana", and UM represents the plots located in the "Vegas Altas del Guadiana" within the region of Extremadura. ns means not significant.

3.2.2. CO_2 Fixed Per Functional Unit

Considering the functional unit (1 kg of fresh tomato) and the productive yield of each plot (Table 1), at the end of the production cycle, the plants were able to accumulate, on average, 0.1905 kg of CO_2 per kg of fresh tomato produced (Figure 2a). There were no statistically significant differences in the observed CO_2 fixation parameter between the different locations sampled from each plant fraction. Figure 2b also shows that, depending

on the cultivars grown, there was also no significance in the CO_2 fixation of the processing tomato. These results can be considered positive, as it seems that the location and the cultivars used do not influence the CO_2 uptake by the totality of the plants.

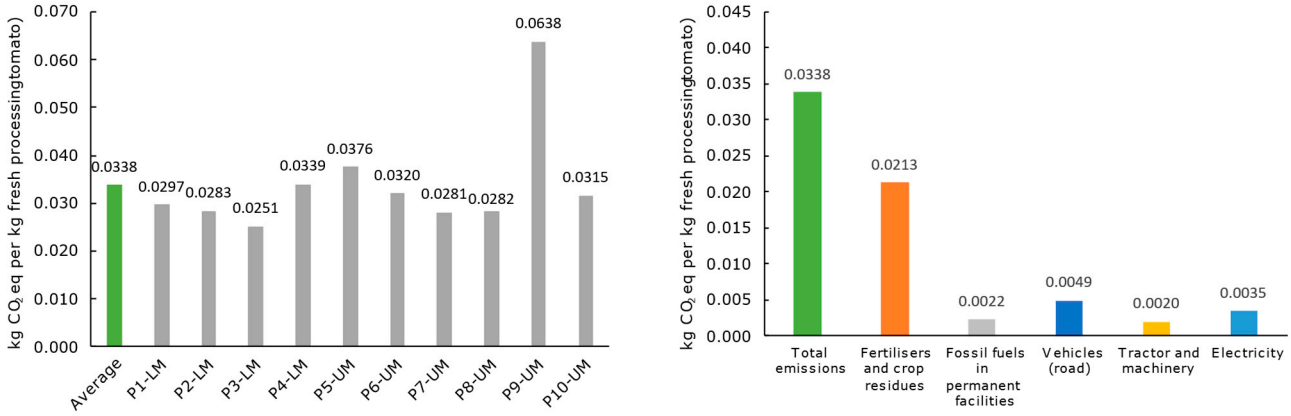


(**a**) (**b**)

Figure 2. CO_2 fixed per functional unit (1 kg of fresh processing tomato) by plants. (**a**) Sampling location and (**b**) Planting cultivars. Significance: ns represents not significant ($p > 0.05$).

3.3. Carbon Footprint of Processing Tomato Crop

The GHG emissions of different locations and processes considered in this study are presented in Figure 3. Taking all data in Table S1 into account, the average emissions of the crop in the 2022 season were 0.0338 kg CO_2-eq kg^{-1} of tomato (Figure 3a). Of these emissions, in processing tomato cultivation, the main source of emissions were fertilisers and crop residue management (63% of the total, Figure 3b). It should be noted that in none of the plots was the burning of crop residues practiced, which is known to be one of the main sources of GHG emissions from agricultural crops [26].



(**a**) (**b**)

Figure 3. Carbon footprints of processing tomato crop per functional unit (1 kg of fresh tomato). (**a**) Sampling location and (**b**) Emission source.

3.4. Sink Effect of Processing Tomato Crop

Bearing in mind only the crop, the average carbon balance of processing tomato crop was 0.1567 kg CO_2 kg^{-1} of fresh tomato produced (Figure 4), obtained from Figures 2a and 3a. There were no significant differences in the average carbon balance between the different locations sampled, and there was a positive balance in all of them. In other words, with the methodologies applied, for each kg of processing tomato produced, an average sink effect of 0.1567 kg CO_2 kg^{-1} was obtained.

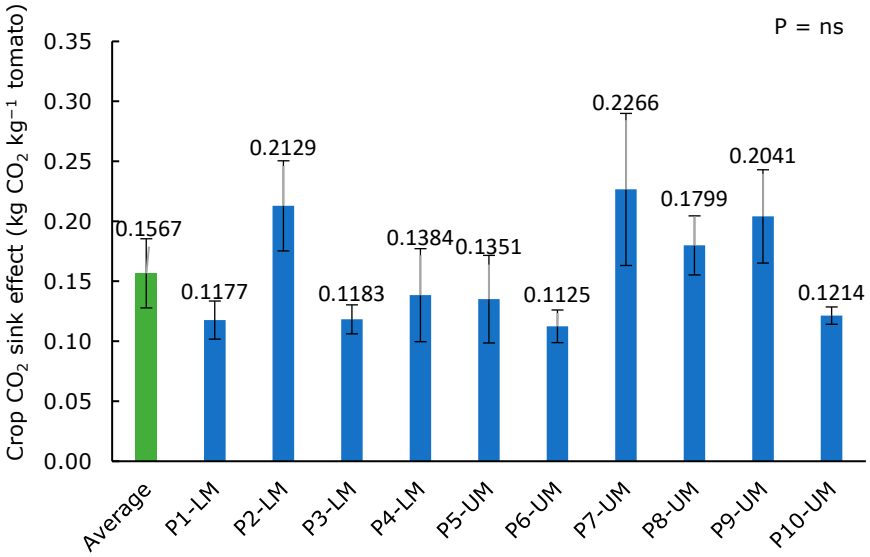


Figure 4. Crop carbon balance of processing tomato plants at each location. Significance: ns represents not significant ($p > 0.05$).

Fresh tomato is the main raw material of the tomato processing industry, being in some cases the only ingredient, as in the case of tomato paste, which is subsequently used in secondary processing industries. In view of this statement and the fact that the crop has a positive carbon balance in this work, it can be considered that this activity can compensate for the emissions of the industry, as shown in Figure 5. In this sense, considering the average value of emissions of the industry from the study by Gutiérrez-Cabanillas et al. [1], the net carbon balance is also positive, with an average value of 0.0900 kg CO_2 kg^{-1} of fresh tomato processed.

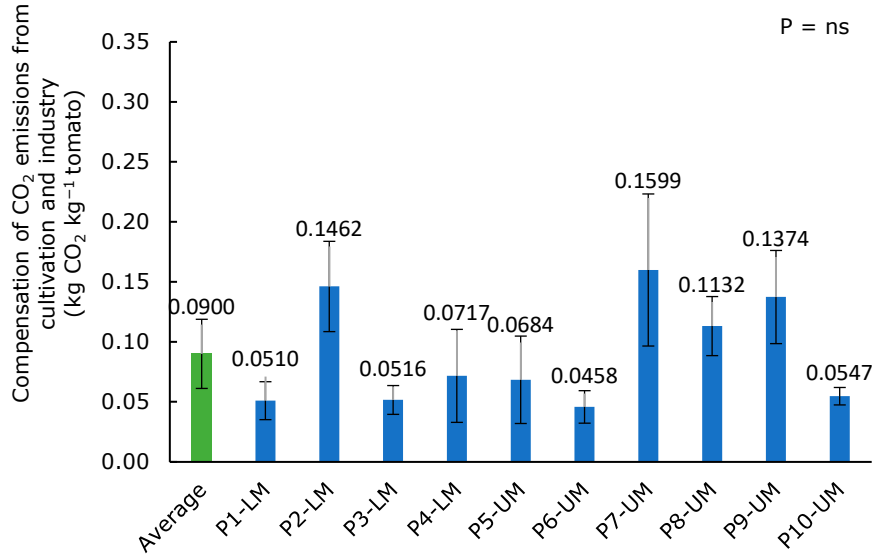


Figure 5. Total carbon balance of processing tomato plants at each location. Significance: ns represents not significant ($p > 0.05$).

4. Discussion

In general, according to the data obtained per plant, we can observe that the tomato crops analysed in this study were highly efficient in terms of CO_2 fixation compared to other similar work using other tomato varieties [27]. The high rate of growth has been reported with optimal environmental conditions and optimal nutrient and water support [28]. On

the other hand, if we take into account that the relation of kg of carbon to kg of dry matter is similar for all varieties, this indicates that, apart from different area conditions, the natural growth ability of these species is a factor that affects CO_2 fixation per plant. Also, CO_2 fixation capacity was high when compared with other horticultural species, such as pepper, melon, or broccoli [29].

Carbon balances calculated by subtracting emissions from the CO_2 fixation by tomato crops are positive in every case. This means that the amount of CO_2 absorbed by the plants was higher than the equivalent CO_2 emissions needed for their production. The carbon balance of the fruit and vegetable production on more than 45.7 hectares of irrigated land studied, after considering emissions generated by the production, transport, and processing of the fruit, was positive. In a recent similar study [30], with tobacco plants grown in an area with similar soil and climatic conditions, results similar to those of this work have been obtained, with tobacco plants being able to compensate for the emissions from their cultivation. It should be noted that the industrial tomato production system is specific, and not all types of open-field tomato production have the same environmental performance. Ntinas et al. [31] showed that industrial tomato production in Southern and Central Europe results in lower GHG emissions (0.1 kg CO_2 eq kg^{-1}) than tomatoes for fresh consumption grown in open fields (0.1 kg CO_2 eq kg^{-1}). These authors also found that emissions from greenhouse fresh tomato crops can be up to 10.1 kg CO_2 eq kg^{-1}. Therefore, other tomato production systems probably do not have the same potential to compensate for GHG emissions as processing tomatoes.

It is important to note that the calculation of this balance does not take into account the full GHG reduction potential of our agriculture. For example, the massive use of synthetic chemical fertilisers in the agro-industry raises concerns such as decreased soil fertility [32] and increased emissions of GHGs [33,34]. The continued pressure on agricultural soil results in the drainage of its nutrients, causing a greater outflow [35]. Because of this, the gradual application of the methodology proposed by organic farming, such as organic matter and compost, is necessary. However, many producers have doubts about their benefits and effectiveness, especially because of the lower yields that are usually obtained with organic farming [36,37], due, among other reasons, to the lower availability of these fertilisers [38,39], which leads to slower plant growth [40,41]. Although it has not been sufficiently demonstrated that organic fertilisers are more nutritious than conventional fertilisers [42–44], it has been observed that their use leads to lower GHG emissions per hectare of crops [45–47]. In this regard, fertilisers used in agriculture are considered to be the largest anthropogenic source of N_20 [48], accounting for 70% of GHGs [49].

On the other hand, it should be noted that burning crop residues significantly increases the carbon footprint of agricultural activity [26]. In the member states of the European Union, the ban on the burning of crop residues is primarily regulated within the measures of the Common Agricultural Policy [50]. The possibility of deviating from this prohibition in exceptional cases has been left open, which is a type of flexibility that exists in Spanish law [51]. Considering these exceptions and the fact that there are no such restrictive regulations in other processing tomato production areas, the authors of this work have carried out a simulation in the calculation of the crop's carbon footprint, assuming that the final destination of the crop residues was burning in 100% of the plots (Supplementary Material, Figure S1). In this simulation, the carbon footprint of the crop would increase significantly, from 0.0338 kg CO_2-eq kg^{-1} of tomato to 0.1200 kg CO_2-eq kg^{-1}, which added to the emissions of the industry, would leave a total net balance of 0.0039 kg CO_2 kg^{-1} of processed fresh tomato. This result can be compared with that obtained by other authors, who have reported that 80–85% of GHGs produced by agricultural activity are due to residue burning [52,53]. In other words, even in the most unfavorable situation, the cultivation of processing tomatoes could compensate for the total emissions of the activity.

However, it is important to note that reduction of burning will not only improve soil conditions and reduce CO_2 emissions into the atmosphere but also damage the soil due to, amongst other factors, the elimination of small insects and micro-organisms in the outer

layers of the soil [54]. In this way, knowing the capacity of processing tomatoes to capture atmospheric CO_2 and the main sources of GHG emissions from the crop (such as residue burning and synthetic nitrogen fertilization), it is possible to work on alternatives that offer greater crop eco-efficiency and lead the way towards completely sustainable agriculture. Therefore, the cost associated with reducing emissions in agriculture is competitive with the cost that such a reduction would represent in other business sectors, such as industry and transport.

Some limitations of the study have to be considered in this work. Firstly, the methodology used does not include Scope 3 (indirect emissions from input suppliers, such as fertiliser production, plant protection products, etc.); therefore, it is not directly comparable with other methodologies, such as Life Cycle Assessment (LCA) [9,55]. However, it is noteworthy that the carbon audits to which the food industry is currently subjected in the EU only include Scope 1 (direct emissions) [56], with the emissions computation carried out in this research having a wider scope. Secondly, the carbon sequestered by plants in the soil has not been assessed and may be important in the total net balance of agricultural activity [57,58]. Another factor in favour of this study is the prevailing production system for processing tomato production in the EU, which is integrated production. This system aims for rational use of agrochemicals and high production yields, which are usually greater than those of organic farming [59], providing two important implications for this study. On the one hand, GHG emissions per functional unit are usually lower in integrated production [60], and biomass production is usually higher, as it is possible to use synthetic fertilisers that are rapidly assimilated by plants [61,62]. Finally, it is important to take into account the high degree of technification of this crop in the study area, which makes it possible to optimise the use of agricultural inputs [63,64], such as irrigation water, fertilisers, and phytosanitary products.

5. Conclusions

In this work, the UNE-ISO 14064-1 [65] methodology has been used to calculate the carbon footprint of the crop. The scope of this methodology may have some limitations, as it does not include Scope 3 of a full Life Cycle Assessment, which would probably increase the GHG emissions obtained in this study. However, the quantification of CO_2 sequestered in the rhizosphere by plants has also not been taken into account, which has a positive effect on the carbon sequestration capacity of plants. Thus, under the conditions of this study, there is a positive net carbon balance considering the cultivation of an annual vegetable crop such as the processing tomato, which can compensate for the emissions of the primary processing industry. Therefore, processing tomato farming can compensate for the GHG emissions of the primary processing tomato industry. These results show that the processing tomato sector can compensate for its own GHG emissions, potentiating a debate about its emission trading system in the EU, as they cannot be compared to those of other types of industries. More research is needed to show that the production process in the primary processing food industry can be sustainable, starting from a raw material whose production results in a positive net carbon balance. These results could enable farmers to achieve sustainable production standards and help the industry comply with EU emissions legislation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agriculture14081267/s1, Table S1. Data required for the calculation of the agricultural carbon footprint (UNE-ISO 14064-1), Table S2. Nitrogen fertilisers applied on each plot, Table S3. Agricultural operations performed on the plots located in the 'Vegas Bajas del Guadiana', Table S4. Agricultural operations performed on the plots located in the 'Vegas Altas del Guadiana', Table S5. Carbon footprint (CF) of the processing tomato industry (Gutiérrez-Cabanillas et al., 2022), Figure S1. Total carbon balance of processing tomato plants at each location if burning of crop residues had been carried out.

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