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Mitigation strategies in the agro-food sector: The anaerobic digestion of tomato purée by-products. An Italian case study

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Highlights

- Tomato processing generates byproducts, whose residual mass is 2–5%.
- Anaerobic digestion is an effective mitigation strategy of environmental load.
- AD of tomato byproducts reduces (max — 13%) the environmental load of tomato purée.
- Environmental credits due to the production of electricity from renewable source
- Use of the heat cogenerated in the AD plant during the tomato processing.

Abstract

Tomato processing involves a significant production of residues, mainly constituted by discarded tomatoes, skins, seeds and pulp. Often, these residues are not valorized and represent an added cost for manufacturing companies because of disposal processes, with environmental issues due to the difficult management. The exploitation of these residual materials results complex as their availability is mainly concentrated in few months. A possible solution is the production of biogas employed in a Combine Heat and Power engine for energy production, in line with the 2020 targets of European Union in terms of promotion of energy from renewable resources and greenhouse gas emission reduction. The tomato by-product utilization for energy production as a strategy to reduce the environmental load of tomato purée was evaluated by means of Life Cycle Assessment. Two scenarios were considered: Baseline Scenario — tomato by-products are sent back to the tomato fields as organic fertilizers; Alternative Scenario — tomato by-products are employed in a nearby biogas plant for energy production. Methane production of tomato by-products was assessed by means of specific laboratory tests. The comparison between the two scenarios highlighted reductions for all the impact categories with the Alternative Scenario. The most important reductions are related to particulate matter (– 5.3%), climate change

(− 6.4%) and ozone depletion (− 13.4%). Although small, the reduction of the environmental impact cannot be neglected; for example for climate change, the anaerobic digestion of by-products allows a saving of GHG emissions that, over the whole year, is equal to 1.567 tons of CO₂ eq.

The results of this study could be up-scaled to the food industries with high heat demand producing considerable amounts of fermentable by-products employable as feedstock for biogas production.

Keywords: Food by-product, Biogas, Italy, Life Cycle Assessment, Residues valorization, Renewable energy.

1. Introduction

Food production, processing, marketing, consumption and disposal have important environmental externalities because of energy and natural resources usage and associated greenhouse gas (GHG) emissions (De Boer et al., 2011, FAO, 2013a, Smith et al., 2014). By 2050, food production will need to be 60% higher than in 2007 (Alexandratos and Bruinsma, 2012) therefore this impact is expected to increase. Broadly speaking, the environmental impacts of food mostly occur during the production and processing phase but considerably environmental effects stem from food by-product and waste management (FAO, 2013b).

In Europe the by-products and residues produced by the most relevant agri-food industries such as olive oil mills, wineries, tomato and fruit processing, are often not valorized or in some cases even wasted. The exploitation of these residual materials results complex for the availability often concentrated in few months and the difficult management of a rather unstable material. The tomato paste manufacturing industry is one of the most important in the food industries. The World Processing Tomato Council (WPTC, 2014), accounting for 95% of world tomato producers, states that annually more than 35 million tons of tomato are somehow processed at global level. Italy is the main processor of industrial tomato in Europe with almost 4.5 million tons of processed tomatoes with a significant production of residues deriving both from tomato cultivation and processing. The industrial processing generates residues from water flumes, washing, sorting table, pulper-refiner and cleaning. In addition, some residues are constituted by the discards of the production line, such as immature, defective or damaged tomatoes. The residual mass can be estimated in about 2–5% of processed product. Wet and dry tomato pomace, constituted by skins, seeds and pulp, is the main part of the residual mass that comes from the pulper (Kaur et al., 2005).

Tomato seeds can be separated from pulp and skin for subsequent oil extraction (Sogi et al., 2003). These residues often represent an added cost for manufacturing companies because of the disposal processes. Alternatively the residues can be sold at low price for animal feeding, given for free to other companies or used as organic fertilizers. In addition, during the storage step of tomato residues, some methane could be produced by uncontrolled anaerobic fermentation. Methane has a strong greenhouse effect and affects the formation of tropospheric ozone as well. Some researchers trying to find a better valorization of these residues highlighted the possibility to obtain a high amount of valuable chemicals such as phenols, lycopene, ascorbic acid, essential amino-acids, carotenoids by means of specific processes (Kaur et al., 2005, Knoblich et al., 2005, Silva et al., 2014, Strati and Oreopoulou, 2014). Other authors focused on the production of biopolymers (Tommonaro et al., 2007) to be employed in the tomato industry or in agriculture. Another possibility is represented by the energetic conversion of these by-products; environmental benefits have been highlighted by many authors as regards the use of food residues as feedstock for anaerobic digestion (Mangut et al., 2006, Dinuccio et al., 2011). The European Union aims to increase biomass-derived energy use in order to achieve the 2020 targets related to raising the share of EU energy consumption produced from renewable resources and reducing greenhouse gas emissions (European Commission, 2009, European Commission, 2010). Small-medium scale Combine Heat and Power (CHP) units fed by biogas produced from residual biomass are strongly incentivized by EU energy and environmental policies (Mangoyana and Smith, 2011) and could also improve waste management in the agri-food sector where the residues are often concentrated in the processing site frequently characterized by a consistent heat demand. Tomato processing residues have been previously characterized from Rossini et al. (2013) by an energy perspective. Anaerobic digestion (AD) of agricultural by-products (e.g., animal slurry, food waste, food processing residues) have been recognized by several studies (Ward et al., 2008, Bacenetti et al., 2013, González-González et al., 2013, Lijó et al., 2014a, Lijó et al., 2014b, Ingraio et al., 2015) as a suitable and effective solution to produce renewable energy by means of a cogeneration systems (electricity — EE and thermal energy — TE). In Italy, thanks to the strong public incentives for electricity generation from biomass currently there are about 1150 AD plants (Negri et al., 2014a). Although most of these plants are fed with cereal silages (González-García et al., 2013, Lansche and Müller, 2012, Bacenetti et al., 2014), after the revision of the subsidy framework the interest about small AD plants (electric power < 300 kW) fed with agricultural by-products and other wastes is increasing (Negri et al., 2014b).

Life Cycle Assessment (LCA) is a systematic method to quantify the environmental impacts of products during the entire production system. LCA is also an interesting tool to identify the hotspots and the mitigation options of environmental loads associated with a production (ISO 14040, 2006, Chiaramonti and Recchia, 2010).

Although originally developed for industrial processes today, LCA is accepted and used also for the evaluation of agricultural activities, where it can be applied to: i) detect the environmental hotspots (processes or activities responsible for the main share of the environmental impacts) and, ii) to compare different processes or different technical solutions that can be implemented in the same process. With regard to the chain of tomato purée production, the aim of this paper is, using the LCA method, to evaluate the environmental burdens of tomato purée and to identify the environmental hotspots. As Alternative Scenario, the benefits arising from the by-product utilization for energy purpose (biogas production) on the environmental burdens of tomato purée were assessed. In more detail, the by-products stemming from tomato processing (i.e., discarded tomatoes, skins and seeds) are used to feed an anaerobic digestion plant in the nearby of the agro-food industry. In addition, the environmental hotspots have been identified throughout production system; AD of tomato by-products is evaluated as a strategy to reduce the environmental load of tomato purée.

2. Materials and methods

2.1 Production system description

The tomato purée production process considered in this paper takes place in the Po Valley area (Northern Italy) and, more precisely, in an agrofood industry located in the District of Lodi (45°19'00"N; 9°16'00"E). Yearly 200.000 tons of tomatoes are processed by the industry. The tomato is mainly cultivated in Lombardy and Emilia Romagna Regions over a global agricultural area in open field of 2800–3000 ha (Bottani et al., 2014).

The local climate is characterized by an average annual temperature of 12.7 °C, and the rainfall is mainly concentrated in autumn and spring (average annual precipitation is equal to 745 mm) (Bacenetti et al., 2014, Negri et al., 2014a, Negri et al., 2014b).

This study has been carried out from a cradle-to-industry gate perspective. In more detail, the LCA model was carried out by including three subsystems (SS): (1) crop cultivation, (2) tomato processing and (3) by-product management.

Subsystem 1 (SS1) involves the cultivation of tomato which can be subdivided into: (1) soil tillage and transplanting, (2) crop growth, (3) harvesting, and (4) transport by

trucks (average distance 40 km). The whole crop cycle takes place during spring and summer seasons (60–75 days), the tomato is harvested from 20 July to 20 September depending on cultivation area, climatic conditions and tomato varieties.

Subsystem 2 (SS2) involves tomato processing at the food industry; it can be divided into: (1) tomatoes unloading, (2) selection and washing (from which derive the wasted tomatoes), (3) chopping, (4) blanching, (5) concentration and refinement (in which the product is subsequently treated with a series of refiners that extract the juice by eliminating skins and seeds), and (6) pasteurization. During SS2 a considerable amount of heat, produced by a natural gas burner, is consumed; in particular, during the blanching high temperature (80–90 °C) is needed in order to inactivate the pectolytic enzymes in the chopped tomato. Subsystem 3 (SS3) involves the management of the by-products arising from Subsystem 2 that are mainly constituted by non-usable tomatoes (about 4000 tons/year) and skins and seeds (about 6000 tons/year). Usually (Baseline Scenario — BS), tomato by-products are sent back to the tomato fields as organic fertilizers (transport carried out by trucks with an average distance of 25 km). In this study, an Alternative Scenario (AS) is evaluated as regards by-product management: the wasted tomatoes, skins and seeds are used to feed an AD plant located close to the agro-food industry (0.1 km). The AD plant has an electrical power of 300 kW, codigesting tomato by-products, other by-products of the same industry (e.g., from pumpkin and pea processing) and animal slurry. As regards tomato by-products, the feeding of the AD plant is based on the use of tomato skins and seeds (storable as silage) during the whole year and of wasted tomatoes only during the tomato harvest season. When the wasted tomatoes are not available the AD plant is fed with other by-products locally available and a little amount of cow slurry as well. The biogas produced is burned in a CHP (Combine Heat and Power) engine; the produced EE is fed into the national electric grid while the ET is partially used to heat the digesters (self consumption; on average 15% of the produced thermal energy). The surplus heat is recovered and used by the agro-food industry itself during the tomato processing (concentration and pasteurization) substituting thermal energy usually generated by burners fed with natural gas.

2.2 Functional unit and system boundaries

The functional unit (FU) provides a reference unit for which the inventory data are normalized (ISO, 14040, 2006). The concept of the functional unit is key in LCA, as it facilitates the comparison of alternative products and/or services (ISO, 14040, 2006).

In this study, the FU is 1 kg of tomato purée. Fig. 1, Fig. 2 show the system boundaries of the tomato purée production system for BS and AS, respectively.

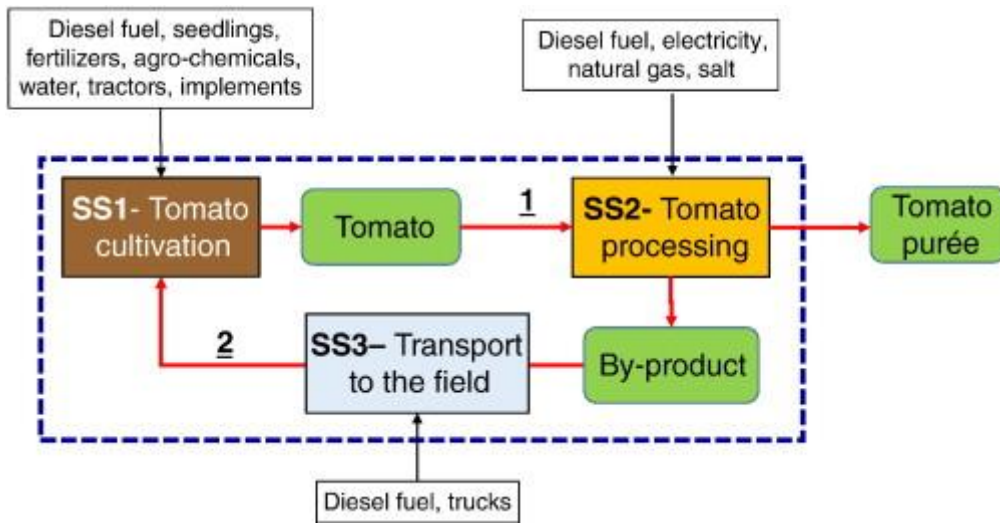


Fig. 1. System boundaries of the tomato purée production system: Baseline Scenario (1: tomato transport to the food industry; 2: by-product transport to the tomato fields).

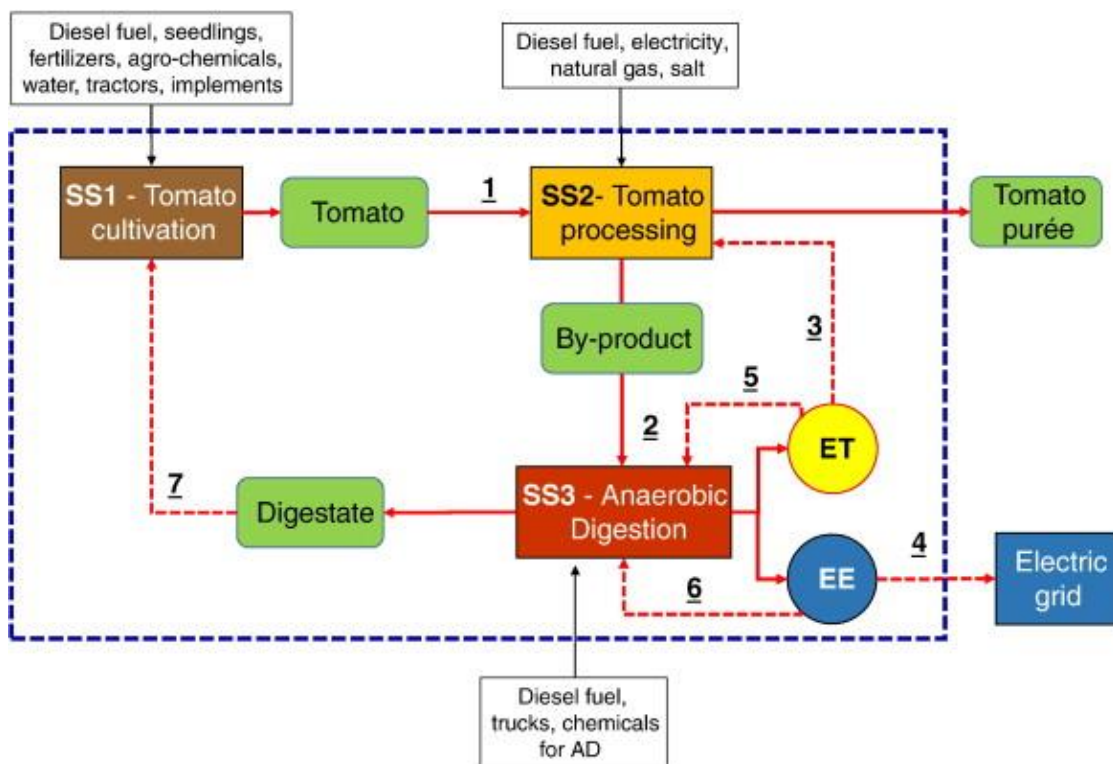


Fig. 2. System boundaries of the tomato purée production system: Alternative Scenario (1: tomato transport to the agro-food industry; 2: AD plant; 3: Surplus ET recovery and used in the agro-food industry; 4: EE fed into the national grid; 5: ET self consumption of the AD plant; 6: EE self consumption of the AD plant; 7: digestate use as organic fertilizer on tomato fields).

In this study, a cradle-to-industry-gate perspective was applied: the core system is the tomato processing; the upstream system involves the cultivation phase and the production of other ingredients (e.g., salt) as well as the packaging materials. The downstream system includes the delivery and distribution of the tomato purée. Both the packaging and the distribution of tomato purée were excluded from the system boundaries as they are common to both the scenarios (BS and AS) considered. For Subsystem 1, the lifecycle of each agricultural process was included within the system boundaries: raw material extraction (e.g., fossil fuels and minerals), manufacture (e.g., seeds, fertilizers and agricultural machines), use (diesel fuel consumption and derived combustion and tire abrasion emissions), maintenance and final disposal of machines, and supply of inputs to the farms (e.g., fertilizers, pesticide and herbicides). Pesticide derived emissions were excluded because of currently no consensus on how their diffusion on the environment must be modeled (Notarnicola et al., 2015). Carbon sequestration by the tomato crops as well as by the soils was not considered because this issue is out of the scope of this study; moreover, its effect on environmental performance of tomato purée will be the same in the two scenario evaluated (Manfredi and Vignali, 2014, Del Borghi et al., 2014). The increase of soil carbon content due to the organic fertilization carried out with tomato by-products or digestate was excluded from the system boundary too. Although, over the long term, the organic fertilization could involve, thanks to the increase of soil organic matter, carbon sequestration, it should be considered that similar effects occur in the two scenarios. In fact, although in the Baseline Scenario, a higher amount of organic matter is applied as organic fertilizer, in the Alternative Scenario the use of digestate involves the distribution of a more stable organic matter (Rehl and Müller, 2011) easily stored into the soil. As regards Subsystem 2 the system boundaries consider energy (heat, electricity and diesel fuel) and material (e.g., salt, water) consumptions as well as the emissions into water and air. For this subsystem, the impact due to the capital goods (e.g., infrastructures) is not considered according to their minor contribution proved by previous LCA studies related to food products (Frischknecht et al., 2007a, Fusi et al., 2014, Siracusa et al., 2014, Notarnicola et al., 2015). Regarding Subsystem 3, in the BS the system boundaries include the tomato transport from the agro-food industry to tomato field and the spreading on the soil; while in the AS are considered: i) the transportation of the tomato by-products to the AD plant, ii) the biomass codigestion; and iii) the biogas use to produce EE and ET (CHP). Capital goods for this subsystem are excluded (Frischknecht et al., 2007a, Frischknecht et al., 2007b).

With regard to EE and ET cogenerated by the AD plant, only the share obtained from tomato by-products was included in the system boundaries. The same approach was applied for the digestate: only the amount derived from the digestion of tomato by-products was included in the assessment (considering its transport and spreading as organic fertilizer in the tomato fields). In other words, while in the BS it is the tomato by-products that are used as fertilizer, in the AS the same role is played by the digestate; the two matrixes have the same content of NPK and therefore can substitute the equivalent amount of mineral fertilizer.

2.3 Inventory analysis

The activities performed in the production system under study were identified by means of interviews, surveys and by literature.

More specifically, for Subsystem 1 (tomato cultivation) information regarding fertilizer and pesticide applications was collected considering the integrated production guidelines of Emilia Romagna and Lombardy (Regione Emilia Romagna, 2014). As regards the field operations, the agricultural processes reported in the database Ecoinvent (Nemecek and Kägi) have been modified considering the characteristics (mass, power, life span, specific fuel consumptions, etc.) of the machines (tractors and implements) used in the tomato fields. In more details, the diesel fuel consumption was estimated by using the model SE³A (Fiala and Bacenetti, 2012) that considers the power requirements of machines, their work capacity and soil characteristics as well. Emissions due to the nitrogen fertilizer applications (nitrate, ammonia, and nitrous oxide) were computed according to the IPCC (IPCC, 2006) and Brentrup et al. (2000). Background data for the production of diesel fuel, fertilizers, and pesticides as well as tractors and implements are taken from the Ecoinvent database v.3 (Althaus et al., 2007, Frischknecht et al., 2007b, Jungbluth et al., 2007, Nemecek and Kägi, 2007, Spielmann et al., 2007) (Table 1).

Table 1. Tomato purée by-product laboratory test results.

| By-products | Dry matter | Volatile solid | Biogas production | Methane | Methane production |
|-----------------|-----------------|-----------------|-------------------------------------|-------------|---------------------------------|
| | % of wet matter | % of dry matter | m ³ /t of volatile solid | % of volume | m ³ /t of wet matter |
| Wasted tomato | 7.8 ± 0.9 | 92.1 ± 2.6 | 506.8 ± 39.7 | 55.2 ± 0.9 | 20.07 ± 1.57 |
| Skins and seeds | 28.1 ± 5.5 | 96.8 ± 2.0 | 358.5 ± 21.9 | 53.7 ± 1.5 | 52.33 ± 3.19 |

For Subsystems 2 (tomato processing) and 3 (by-product management), the data about energy and material consumptions as well as about the availability of by-products and the transport distances were provided by the agro-food industry. Emissions from natural gas combustion in burner were evaluated considering the emission factors reported by EEA (2013).

About the AD plant, all the information needed for the assessment were collected by means of surveys in similar plants fed with agro-food by-products and cereal silages and of previous studies (Bacenetti et al., 2013, Bacenetti et al., 2014, Lijó et al., 2014a, Lijó et al., 2014b, Whiting and Azapagic, 2014). In more details, the net EE produced by the tomato by-products over the year was calculated considering their methane potential, the electric energy efficiency of the CHP and the electric self consumption.¹ The ET recovered by the AD plant and used by the agro-food industry was evaluated taking into account the heat production and self consumption.²

Data about chemical characterization of tomato purée by-products as well as about their methane potential were obtained by specific laboratory tests. For 30 samples of by-products (15 for wasted tomato and 15 for skins and seed), the methane potential (m³ of CH₄ for tonne of by-product digested) was evaluated in Lab-scale unstirred fermenters placed in thermostatic baths at 40 °C (Negri et al., 2014a). The inoculums were collected from different full scale AD plants. The achieved results are shown in Table 2.

Table 2. Different Ecoinvent unit processes involved in the inventory for SS1.

| Process and input | Ecoinvent process |
|------------------------------|--|
| Organic fertilization | Slurry spreading, by vacuum tanker/CH U ^a |
| Tillage operation | Tillage, ploughing/CH U ^a |
| | Tillage, harrowing, by rotary harrow/CH U ^a |
| Transplanting | Sowing/CH U ^a |
| Mineral fertilization | Fertilizing, by broadcaster/CH U ^a |
| Mechanical weed control | Hoeing/CH U ^a |
| Irrigation | Irrigating/ha/CH U ^a |
| Harvest | Harvesting, by complete harvester, beets/CH U ^a |
| Plant protection application | Application of plant protection products, by field sprayer/CH U ^a |
| Transport to food industry | Transport, lorry > 32 t, EURO4/RER U |
| Mineral fertilizers | Fertilizer (N) |
| | Fertilizer (P ₂ O ₅) |
| | Fertilizer (K ₂ O) |
| Herbicides | Metolachlor, at regional storehouse/RER U |

| Process and input | Ecoinvent process |
|-------------------|---|
| | Pesticide unspecified, at regional storehouse/RER U |
| | Propachlor, at regional storehouse/RER U |
| | Bipyridylum-compounds, at regional storehouse/RER U |
| Diesel fuel | Diesel, at regional storage/RER U |
| Lubricant oil | Lubricating oil, at plant/RER U |
| Tractors | Tractor, production/CH/I U |
| Operative machine | Agricultural machinery, general, production/CH/I U |

a

Field operations have been modified considering site specific parameters (recorded by the farmer or by means of the surveys at the farm) as regards: working time, fuel and lubricant oil consumptions, annual use and lifespan of tractors and operative machines.

According to Frischknecht et al. (2007b) the impact of capital goods was considered when the maintenance and depreciation costs of capital equipment form a substantial part of the product price. Therefore, only the environmental load of capital goods of SS1 is included.

2.4 Allocation

Within the BS two types of products are produced: tomato purée and two by-products, namely wasted tomatoes and skin and seeds. Even though the BS consists of a multifunctional process, no allocation was taken into account, since tomato by-products are simply reused as organic fertilizer in the tomato field. In the AS, besides the tomato purée and tomato by-products, EE and ET are also generated. In this case, a system expansion approach was applied: tomato by-products are used to feed an AD plant, which in turn produces EE and ET. The production of EE avoids the generation (and associated impacts) of EE from other sources (i.e., Italian electric mix), while the ET obtained from the AD plant is in part used for the tomato purée production process. Therefore, while in the BS the total amount of ET is totally provided by a natural gas burner, in the AS only a part of ET is produced from natural gas.

2.5 Impact assessment

Among the steps defined within the Life Cycle Impact Assessment phase of the standardized LCA methodology, only classification and characterization stages were undertaken (ISO, 14040, 2006). The characterization factors reported by the ILCD method were used (Wolf et al., 2012). The following nine impact potentials were evaluated

according to the selected method: climate change (CC), ozone depletion (OD), particulate matter (PM); photochemical oxidant formation (POF); acidification (TA), freshwater eutrophication (FE), terrestrial eutrophication (TE), marine eutrophication (ME), and mineral, fossil and renewable resource depletion (MFRD). Due to the uncertainties about the definition of characterization factors for many active ingredients, the toxicity-related impact categories were not evaluated (Sleeswijk et al., 2008). The software SimaPro was used for the computational implementation of the inventories (Goedkoop et al., 2010).

2.5.1 Sensitivity analysis

In order to test the robustness of the results, a sensitivity analysis was carried out on the system under study. A set of parameters was changed, and its influence on the results was evaluated. The parameters that were taken into account to run the sensitivity analysis are:

- i) in the BS, the transport distance of tomato by-products; the average distance from the food industry to the tomato field, set to 25 km in the BS was increased to 40 km and decreased to 10 km,
- ii) in the AS, the specific biogas productions of tomato by-products, to this regard the standard deviations recorded in the laboratory tests were considered to increase and decrease the average values reported in Table 1;
- iii) in the AS, the crediting of the electricity cogenerated by the CHP in the AD plant as electricity from coal instead of the Italian electric mix.

3. Results and discussion

3.1 Baseline Scenario (BS)

3.2 Alternative Scenario: by-product as feedstock for AD plant

Table 4 reports the results about the environmental performance of tomato purée achieved considering the anaerobic digestion of tomato by-product. Fig. 6 highlights the contribution of the three different subsystems; the energetic valorization of by-products involves an environmental benefit for all the impact categories evaluated. This benefit is low (< 3%) for AP, FE, TE, ME and MFRD while it is higher for POF (− 3.30%), PM (− 5.38%), CC (− 6.29%) and OD (− 13.16%).

Table 4. Environmental results for the FU in Alternative Scenario (anaerobic digestion of byproducts) and comparison with Baseline Scenario.

| Impact category | Acronym | Environmental impact | |
|--|---------|---------------------------------------|------------------------------|
| | | Score | Variation with respect to BS |
| Climate change | CC | 0.241 kg CO ₂ eq. | - 6.37% |
| Ozone depletion | OD | 1.21 · 10 ⁻⁸ kg CFC-11 eq. | - 13.39% |
| Particulate matter | PM | 6.26 · 10 ⁻⁵ kg PM2.5 eq. | - 5.28% |
| Photochemical ozone formation | POF | 0.875 g NMVOC eq. | - 3.45% |
| Acidification | AP | 0.0021 molc H + eq. | - 2.56% |
| Terrestrial eutrophication | TE | 0.0088 molc N eq. | - 1.15% |
| Fresh water eutrophication | FE | 6.06 · 10 ⁻⁷ kg P eq. | - 2.67% |
| Marine eutrophication | ME | 0.594 g N eq. | - 1.52% |
| Mineral, fossil & ren resource depletion | MFRD | 1.43 · 10 ⁻⁶ kg Sb eq. | - 1.54% |

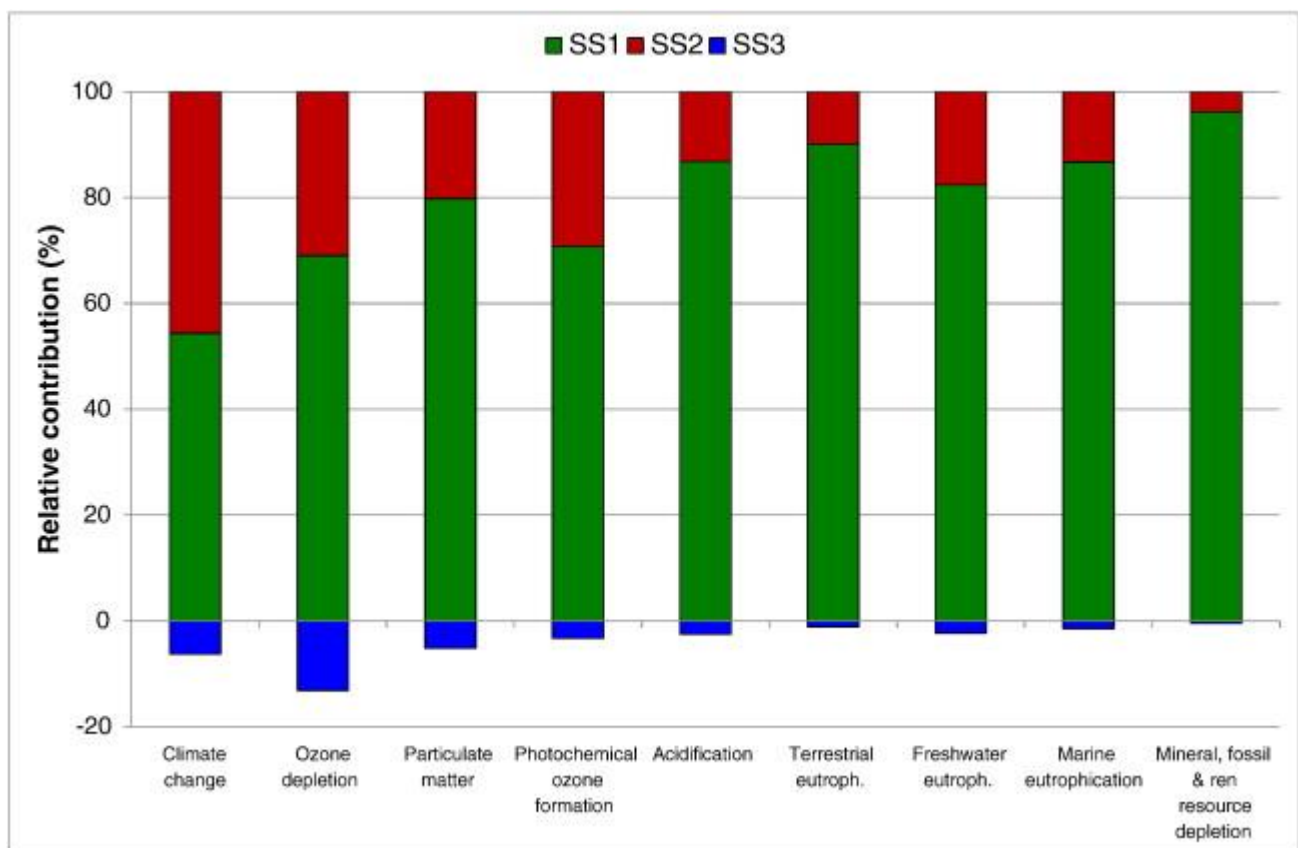


Fig. 6. Hotspot identification for the Alternative Scenario.

3.3 Comparison between the two scenarios

The comparison among BS and AS is shown in Fig. 7.

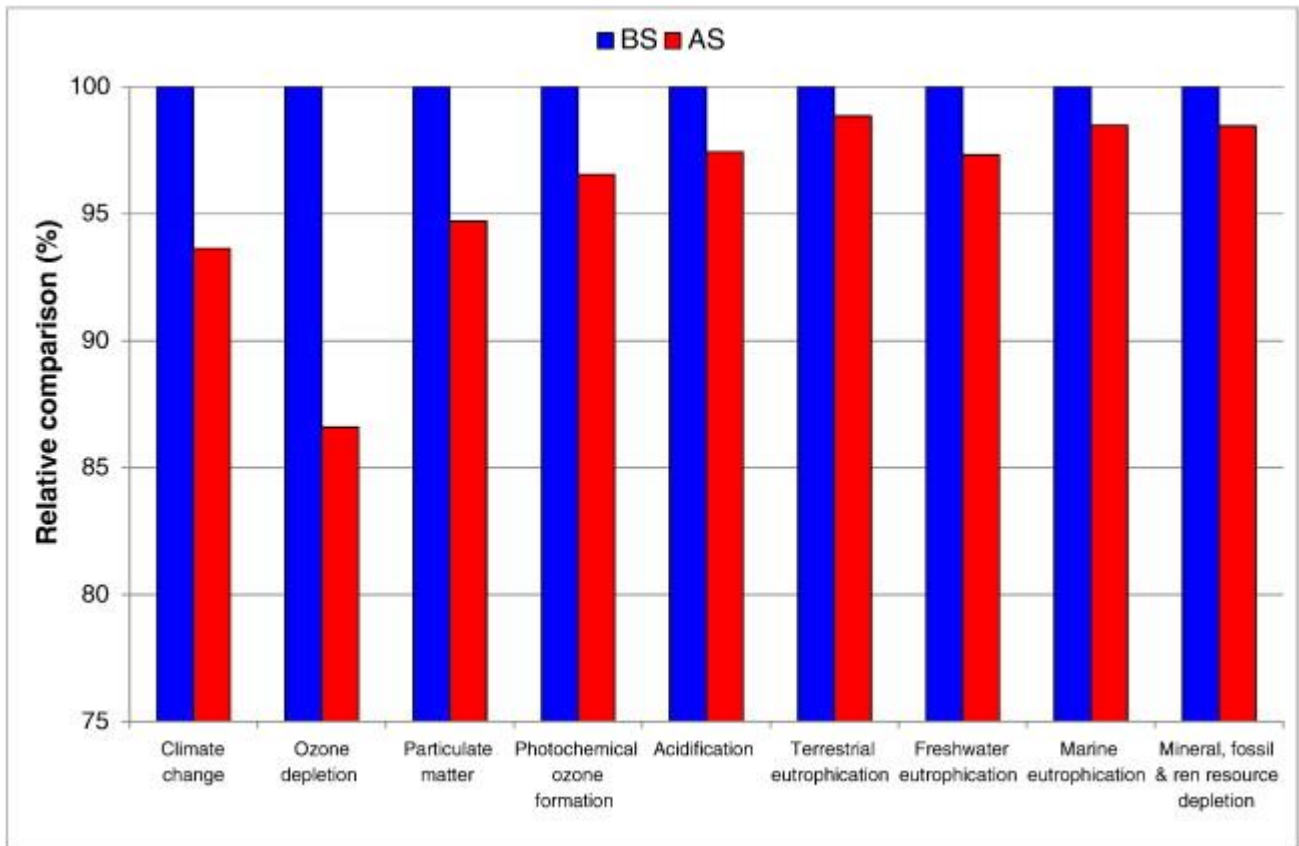


Fig. 7. Comparison among the environmental impact of 1 kg of tomato purée considering the two different management solutions for tomato by-products.

For all the nine evaluated impact categories the AS shows better environmental performances than the BS; the AD of tomato by-products allows a reduction of the environmental load of tomato purée. This reduction is quite variable for all the impact categories; in more details it is little ($< 3.0\%$) for AP, TE, FE, ME and MFRD while it is higher for POF ($- 3.5\%$), PM ($- 5.3\%$), CC ($- 6.4\%$) and OD ($- 13.4\%$).

The utilization of tomato by-products to feed an AD plant reduces moderately (max — 13%) the environmental load of tomato purée; nevertheless it can be highlighted that the impact is reduced for all the evaluated impact categories. Although small, the reduction of the environmental impact cannot be neglected; for example for CC, the AD of by-products allows a savings of GHG emission of about 7%.

The environmental benefits due to valorization of tomato by-products arise from the credits due to the production of electricity from renewable source that avoid the generation from fossil fuels and, secondarily, from the valorization during the tomato processing (SS2) of the heat cogenerated by the biogas CHP.

The lower reductions of the environmental load are achieved for impact categories more affected by the SS1. In fact, AP, TE, FE and ME are mainly related to the emissions due to fertilizer applications (leaching of nitrate, ammonia volatilization,

dinitrogen oxide production, phosphorus runoff) while for MFRD the transport of tomato from field from the agro-food industry represents the main hotspot. Table 5 reports the results of the sensitivity analysis. For AS, all the evaluated cases (the variation of methane production from by-products as well as the substitution of the EE produced at the AD plant with electricity from coal) determine an environmental benefit. When the electricity produced is supposed to replace EE from coal (instead of the Italian electricity mix), the reduction is higher with respect to BS for all the evaluated impact categories except for OD. The variation of by-product methane production slightly affects (< 1%) the environmental burdens of tomato purée. As regards the BS, the changes of the by-product transport distance (increased from 25 to 40 km and reduced from 25 to 10 km) involve a variation of the environmental load of the FU lower than 1% except for MFRD that increases by 1.1% when the distance is extended at 40 km.

Table 5. Results of the sensitivity analysis: the variations are expressed with respect to BS assessed considering a by-product transport distance equal to 25 km).

| Impact category | BS | | AS | | | |
|--------------------------------------|-------------------------------|---------|--------------------|----------|-------------|-----------|
| | By-product transport distance | | Methane production | | Electricity | |
| | 10 km | 40 km | Min | Max | ITA mix | From coal |
| Climate change | - 0.04% | + 0.09% | - 6.15% | - 6.59% | - 6.37% | - 8.38% |
| Ozone depletion | - 0.13% | + 0.26% | - 13.03% | - 13.75% | - 13.39% | - 8.56% |
| Particulate matter | - 0.06% | + 0.11% | - 4.98% | - 5.58% | - 5.28% | - 9.05% |
| Photochemical ozone formation | - 0.08% | + 0.16% | - 3.29% | - 3.61% | - 3.45% | - 6.05% |
| Acidification | - 0.03% | + 0.06% | - 2.42% | - 2.71% | - 2.56% | - 5.45% |
| Terrestrial eutrophication | - 0.03% | + 0.05% | - 1.09% | - 1.20% | - 1.15% | - 2.31% |
| Freshwater eutrophication | - 0.20% | + 0.41% | - 2.58% | - 2.77% | - 2.67% | - 3.76% |
| Marine eutrophication | - 0.04% | + 0.07% | - 1.44% | - 1.59% | - 1.52% | - 2.95% |
| Mineral, fossil & ren resource depl. | - 0.55% | + 1.10% | - 1.52% | - 1.56% | - 1.54% | - 1.76% |

4. Conclusions

Over the last years, the interest in the environmental impacts associated with food systems has strongly grown. Several studies have confirmed the relative importance of “food and beverages consumption” in contributing to environmental impacts. Within the food chain, also the waste management processes contribute to the overall

environmental burden of food products (FAO, 2013b). Among the different mitigation strategies, several studies highlighted that anaerobic digestion of by-products from agro-food sector is an effective solution (De Boer et al., 2011, Smith et al., 2014) to reduce GHG emissions from agricultural activities and food processing. Moreover, the feeding of the AD plants with by-products and wastes instead of improving the environmental performance of the electricity produced in particular as regards impact categories such as eutrophication and acidification (Lijó et al., 2014a, Lijó et al., 2014b).

The study undertaken evaluates, from an environmental point of view, two different by-product management systems in the tomato industry: the first scenario (BS) represents the current situation of the company involved in the analysis; the second scenario (AS) is instead a potentially applicable alternative. The latter consists in fact in the utilization of the tomato by-products to produce energy by means of an AD plant. Such solution implies lower impacts with respect to the BS. Even though this reduction is small, it concerns all the impact categories considered. Moreover, the energetic valorization of tomato by-products is carried out by means of a technical solution (the anaerobic digestion) that is already well known and accepted in the European agro-food sector; it is technologically mature and benefits from high public subsidy (Bacenetti et al., 2013, Ingraio et al., 2015)

As regards the integration of the use of by-products generated during the food processing for energy production, the results of this study could be upscaled to the agro-food industries that process vegetables and fruits producing considerable amounts of fermentable by-products and have high heat consumption. In fact, this kind of biomass could be similarly employed as feedstock for biogas production, optimizing the agro-food industry and adding further environmental benefits, currently very important also under the commercial point of view.

On the other hand, regarding the AD, the use of agro-food by-products instead of cereal silages (characterized by a high impact with regard to impact categories such as acidification and eutrophication) could improve the sustainability of the whole biogas-to-electricity process, reduce the economic expenses for feedstock supply and, finally, enhance the acceptability of this important renewable energy sources.

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