



A life cycle assessment of biosolarization as a valorization pathway for tomato pomace utilization in California



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ABSTRACT

The California tomato processing industry produced circa 388,856 t of tomato pomace in 2014. While currently used for animal feed, tomato pomace could be utilized for biosolarization. Primary Energy Demand (PED) and Global Warming Potential (GWP) equivalent emissions were calculated for two valorization pathways: (i) feed for cattle; and (ii) biosolarization. In order to make these two valorization pathways comparable three management options were analyzed whereby each part of the system was satisfied, i.e. a pest management sub-system and a cattle feed sub-system. The management options were (1) tomato pomace used for cattle feed and soil pest control using fumigant Telone II and herbicide glyphosate; (2) tomato pomace used for cattle feed and soil pest control using solarization; (3) alternative cattle feed (cottonseed, canola pellets and wheat straw) and soil pest control using biosolarization with tomato pomace. Options 2 and 3 result in a reduction of GWP and PED. Among management options, the GWP ranged from 64–98 kg CO₂-e and 1502–2250 MJ for PED per t of pomace. The majority of impacts were beyond the tomato processors' immediate control, therefore encouraging the diversion of tomato pomace to biosolarization may be desirable. Total savings per annum for biosolarization could be as large as 7.7 M kg CO₂-e and 203,000 GJ annually.

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1. Introduction

The extensive use of pesticides in modern agricultural systems is essential in order to manage pests that transmit infectious diseases and compete for resources. Approximately 2.5 Mt of pesticides are used worldwide, with over 450 Kt used in the United States of America (USA) each year (Alavanja, 2009). Until recently, Methyl bromide (MeBr) was the most widely used pesticide, however in accordance with the Clean Air Act (EPA, 2016) its use has been banned due to its negative effect on human health and depletion of the ozone layer (UNEP, 1992). The prohibition of MeBr has spurred

innovative new designs and formulations of pesticides by manufacturers and researchers to meet the global demand for pest control in agriculture. Alternative and sustainable integrated pest management strategies need to have a low environmental impact, be cost effective (Lichtfouse et al., 2009), and ideally, they should only be toxic to the target organisms (Ros et al., 2008).

One alternative approach to chemical pesticides use is solarization; a hydrothermal process of disinfecting soil of agricultural pests. Solarization is accomplished by covering moist soil with clear plastic sheeting, leading to passive solar heating and pest inactivation through a combination of physical, chemical, and biological mechanisms (Stapleton, 2000). Solarization has been shown to be beneficial and practical (Özhan Boz, 2009), in particular for strawberry (Yildiz et al., 2010) and legume cultivation (Linke et al., 1991), and in smaller farming operations (Stapleton et al., 2008). However,

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there are barriers preventing its widespread use. Solarization demands strict scheduling to coincide with the warmest period of the year, and it suffers from variable efficiency (Stapleton, 2000). The addition of a soil amendment with organic matter extends solarization to the process known as biosolarization, and has been shown to enhance pest-inactivating conditions (Achmon et al., 2016; Simmons et al., 2013) while contributing to the mitigation of the aforementioned barriers. Biosolarization and solarization research to date has focused on the technical aspects of the technology with an emphasis on comparing the pest control efficacy to conventional pesticides (Özhan Boz, 2009; Achmon et al., 2016; Simmons et al., 2013). Typically, the soil amendment used in biosolarization is an agricultural by-product or residue. The use of agricultural by-products and residues for waste valorization processes is seen as an opportunity to displace fossil alternatives (Lin et al., 2013) and falls within the mandate of the bioeconomy, whereby non-renewable products are replaced with renewable alternatives.

One location where the adoption of biosolarization is ideal due to its climate and significant agricultural industry is the state of California (CA), USA. Annually, CA produces large quantities of fruit processing residues (Morning Star, 2014) and also requires soil pest management for a significant area of agricultural land (Epstein and Zang, 2014). Solid residues from fruit processing are a promising biosolarization organic amendment because they are rich in organic compounds and have limited alternate uses (Achmon et al., 2016). Pomace consists mainly of skins, seeds and residual pulp that remain after the fruit has been disrupted and pressed. Achmon et al. (2016) identified that for biosolarization, tomato pomace gave the best result, while white grape pomace performed less effectively and red grape pomace was far less suitable.

Research has been carried out on tomato processing in CA (Brodt et al., 2013), but did not include options for the management of tomato pomace. In 2007, about 260,000 t (fresh weight) of tomato pomace was produced by the California tomato processing industry (Matteson and Jenkins, 2007), which had increased to approximately 388,856 t (fresh weight) by 2014 (Morning Star, 2014). The majority of agricultural by-products are incorporated by dairy farmers into their feed rations (Silva-del-Rio et al., 2010), and tomato pomace has been successfully used as a component of the ration in some California dairies (Cassinero et al., 2015). If tomato pomace were to be diverted to biosolarization, an ideal location would be the San Joaquin Valley, one of CA's major eggplant cultivation regions (Aguilar, 2016), and where many of the tomato processors operate. Eggplant is often harvested in the summer in this region, leaving the fields fallow during the warmer months that are ideal for biosolarization. This also corresponds to the tomato-processing season and thus the availability of pomace. Several pesticides are typically used (CEPADPR, 2016) to control soil borne pests in eggplant fields. These factors make eggplant production an ideal target for alternative pest management technologies like biosolarization.

Life cycle assessment (LCA) is a technique that quantifies the potential environmental impact and resource consumption of a product, system or service from cradle to grave (ISO, 2006). The LCA method can be employed to assess the environmental impact of utilizing tomato pomace for biosolarization. To date no LCA has been published on solarization, biosolarization, or tomato pomace management; however, LCA studies have been carried out that look at the valorization of wasted food products, food residues and crop residues (San Martin et al., 2016; Gassara et al., 2011). The approach taken by both San Martin et al. (2016) and Gassara et al. (2011) was to consider these organic materials as wastes (wasted vegetables and apple pomace, respectively) that would have otherwise been sent to landfill, hence they omitted the upstream impact and only considered the recovery phase. For simplicity, this study followed

the same established approach. Such studies considered competing valorization pathways, but did not expand the systems so that value-added products produced where comparable, and all parts of the system were equally satisfied.

The objective of the study was to evaluate the implications, in terms of global warming impact and fossil energy consumption, of utilizing tomato pomace for biosolarization rather than as a component of livestock diets in the context of soil fumigation prior to eggplant crop establishment in California.

2. Materials and methods

2.1. Life cycle assessment

A LCA study was carried out based on ISO 14040 standard (ISO, 2006) and the four stages were followed (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. GaBi v.6 software (Thinkstep, 2016) was used for modelling. The Centrum voor Milieuwetenschappen (CML) 2001 baseline methodology (Guinee et al., 2002) was used without normalisation or weighting, and included the environmental impact global warming potential (GWP, kg CO₂-e) and primary energy demand (PED, MJ).

2.1.1. Goal and scope definition

The goal of the study was to calculate baseline environmental data for utilizing tomato pomace as a substrate for biosolarization, from the perspective of waste management/valorization as compared to use as an animal feed ingredient.

The reason for undertaking this study was to support strategic decision-making and the audience was assumed to be the scientific community, tomato processors, regulators and farmers.

Two valorization pathways for tomato pomace (Table 1) were identified for California: (i) feed for cattle (the business as usual option); and (ii) biosolarization. In order to make these two valorization pathways comparable three hypothetical management options were constructed whereby each part of the system was satisfied, i.e. a pest management sub-system and cattle feed sub-system. The management options were (1) tomato pomace used for cattle feed and soil pest control using the fumigant Telone II and herbicide glyphosate; (2) tomato pomace used for cattle feed and soil pest control using solarization; (3) alternative cattle feed (cottonseed, canola pellets and wheat straw) and soil pest control using biosolarization with tomato pomace.

2.1.1.1. Option 1: business-as-usual (BaU), tomato pomace for cattle feed and pest control with chemical fumigant. Option 1 represents BaU (Fig. 1), whereby tomato pomace is transported from 19

Table 1

Physiochemical characteristics of Tomato Pomace, Cottonseed (whole, with lint), Canola Pellets and Wheat Straw (given as % dry weight except where noted); (Beef Magazine, 2010).

Constituent	Tomato pomace	Cottonseed	Canola pellets	Wheat straw
Fat	10.6	19.4	2	1.8
Protein	23	23	41	3
Carbohydrate	3.78	—	—	—
Fibre	50	37	19	57
Ash	6	5	8	8
Water ^a	77	9	10	9
Nitrogen	3.68	3.68	6.56	0.48
Phosphorus	0.59	0.64	1.14	0.06
Potassium	3.6	1	1.1	1.3
Carbon (total)	55.3	—	—	—

^a Fresh weight.

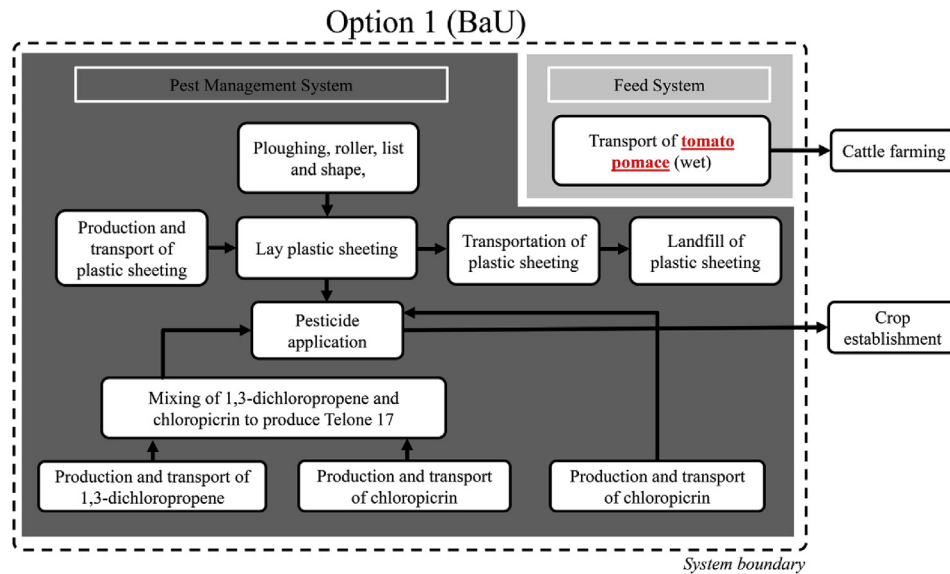


Fig. 1. System diagram and boundary for Option 1.

locations (Table 2) in CA, to Tulare County, CA, where it is utilized as a cattle feed ingredient (feed system).

For the pest management system, the norm is the use of chemical pesticide. Prior to pesticide application, the soil must be prepared. This includes ploughing, rolling and shaping using a tractor and associated machinery. The crop eggplant, which is common to Fresno County, CA, was chosen in order to calculate how much land is treated with pesticide per ha⁻¹. Pest control was then carried out and is achieved by using Telone C17 (a combination of 1,3-dichloropropene and chloropicrin) and glyphosate. It was assumed that 1,3-dichloropropene was produced in Freeport, Texas (DOW, 2008), and chloropicrin was produced in Nicklor, Long Beach, CA (US ITC, 2010). The mixing of 1,3-dichloropropene and chloropicrin to produce Telone C17 was assumed to happen in Freeport, Texas (DOW, 2008). It was assumed that glyphosate was produced in Luling, Louisiana (Monsanto, 2010). Both products

would then be transport via train to Fresno, CA where they are applied. During pesticide application plastic sheeting is used in order to trap the substance. Once used, the plastic sheeting waste is transported to landfill, which is the current norm for agricultural plastics in CA.

2.1.1.2. Option 2: tomato pomace for cattle feed and pest control with solarization. For Option 2 (Fig. 2) tomato pomace is utilized in the cattle feed system and is transported from 19 locations (Table 2) in CA, to Tulare County, CA.

For the pest management system it was assumed that solarization was implemented. Prior to solarization, the soil must be prepared. This includes ploughing, rolling and shaping using a tractor and associated machinery. As per Option 1, the crop eggplant was chosen in order to calculate how much land is solarized per ha⁻¹ (Fresno County, CA). During solarization, plastic

Table 2
Locations of tomato processing centres in California.

Location	Pomace production (metric tonnes, fresh weight)	Pomace production (metric tonnes, dry weight)	Distance to Fresno (horticulture) (km)	Distance to Tulare (feed) (km)
Santa Nella	50,808	11,686	408	476
Williams	43,245	9946	370	438
Los Banos	38,164	8778	117	185
Huron	29,561	6799	85.8	72.5
Lemoore	25,866	5949	54.1	49.4
Los Banos	23,672	5445	117	185
Bakersfield	23,383	5378	176	103
Corcoran	19,226	4422	81	29.6
Los Banos	18,995	4369	117	185
Dixon	17,436	4010	310	363
Woodland	17,090	3931	307	375
Firebaugh	14,434	3320	69.1	137
Williams	14,376	3307	370	438
Oakdale	11,894	2736	165	232
Helm	11,894	2736	47.5	90.1
Stockton	9873	2271	205	273
Stockton	9527	2191	205	273
Hanford	5081	1169	53.7	36.6
Modesto	4330	996	156	224
Total	388,856	89,437	—	—
Average	—	—	179.7	219.2

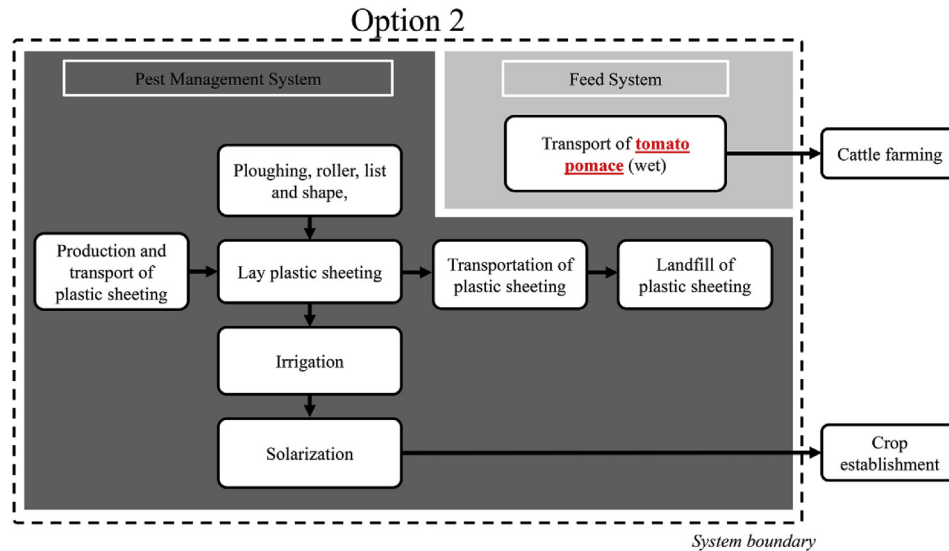


Fig. 2. System diagram and boundary for Option 2.

sheeting is used to achieve passive solar heating and pest inactivation in conjunction with irrigation, which is carried out to keep the soil moist. Once solarization is complete, the plastic sheeting waste is sent to landfill, which is the current norm in CA.

2.1.1.3. Option 3: a mix of cottonseed, canola pellets and wheat straw for cattle feed and pest control with biosolarization utilizing tomato pomace. For Option 3 (Fig. 3), for the cattle feed system, tomato pomace was replaced as a feed ingredient with the most likely alternative (cottonseed, canola pellets and wheat straw) to achieve the net energy of lactation, crude protein, neutral detergent fiber, and ether-extractable fat requirements for cattle feed, in Tulare County, CA, in the San Joaquin Valley.

For the pest management system it was assumed that biosolarization was carried out, whereby tomato pomace is transported from 19 locations (Table 2) in CA, to Fresno County, CA., where it is utilized. The tomato pomace is spread via a tractor, after which the soil is prepared. This includes ploughing, rolling and shaping using a tractor and associated machinery. The crop eggplant was assumed, which is common to Fresno County, CA. During biosolarization plastic sheeting is used to achieve passive solar heating and pest inactivation in conjunction with irrigation, which is carried out to keep the soil moist. Once biosolarization is achieved, the waste plastic sheeting is sent to landfill, which is the current norm in CA.

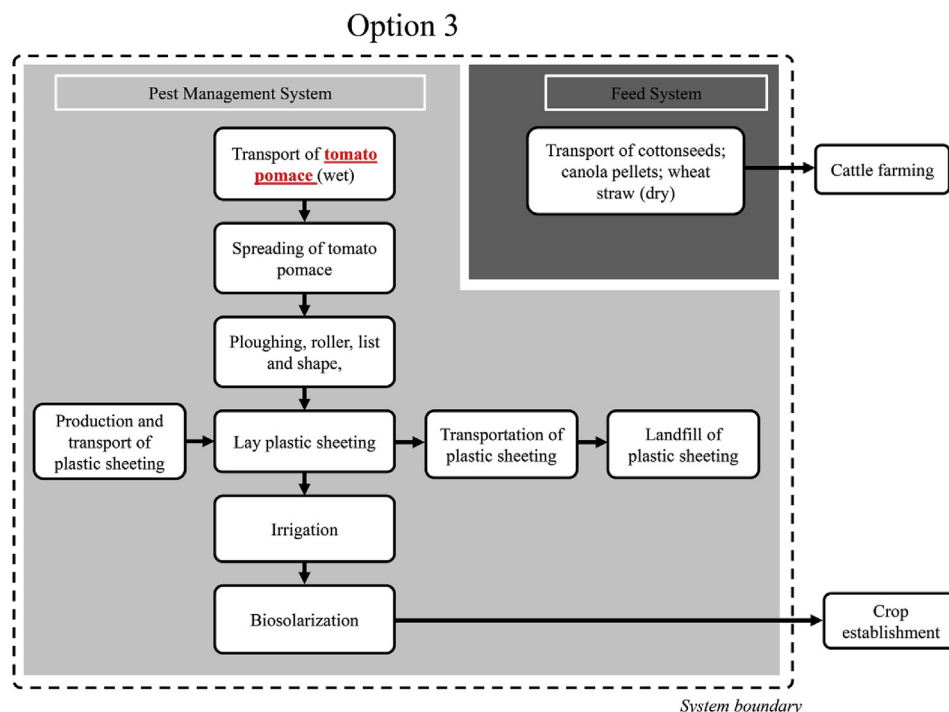


Fig. 3. System diagram and boundary for Option 3.

2.1.2. Functional unit

The functional unit (FU) was the management of 1 t of tomato pomace. The reference flow was the annual amount of tomato pomace produced in California in 2014 (i.e. 388,856 t fresh weight), which was calculated from industry tomato crop and processing capacity data (Morning Star, 2014) and measured values for pomace yield and moisture content (Del Valle et al., 2006).

2.1.3. System boundary

The system boundary for all three options include a feed system and a pest management system in order allow for comparison (Figs. 1–3). The upstream burden was excluded for the feed system and the starting point of the analysis was transportation of feed from a processing facility, while the downstream boundary for the feed system was curtailed before cattle production. For the pest control system the downstream boundary was curtailed prior to crop establishment.

2.1.4. Contribution and sensitivity analysis

A contribution analysis was carried out by relevant process for each option and included: fumigant production, herbicide production, transport (fumigant/tomato pomace/alternative feed), spreading (pomace), ploughing, roller, list and shape, plastic sheeting production, laying of plastic sheeting, irrigation, solarization, biosolarization, fumigation, herbicide application, plastic sheeting removal and transport of plastic sheeting to landfill and landfill of plastic sheeting.

A sensitivity analysis was carried out for all three options for GWP using a $\pm 10\%$ adjustment of activity data and parameters. For Option 1 the changes made were: fumigant production impact, herbicide production impact, transport distances (herbicide and fumigant), fuel consumed for all agricultural processes, plastic sheeting used (production and landfilled), transport of plastic sheeting waste, transport of feed (tomato pomace). For Option 2 the changes made were: fuel consumed for agricultural processes (except irrigation), fuel consumed during irrigation, plastic sheeting used (production and landfilled), transport of plastic sheeting waste, transport of feed (tomato pomace). For Option 3 the changes made were: transport distances (tomato pomace), fuel consumed for all agricultural processes (except irrigation), fuel consumed during irrigation, plastic sheeting used (production and landfilled), transport of plastic sheeting waste, transport of alternative feed (cottonseed, canola pellets and wheat straw).

2.2. Life cycle inventory

Life cycle inventory data was gathered from observed field and laboratory data from experiments carried out at the University of California, Davis in Davis, CA and at the UC Kearney Agricultural Research and Extension Center in Parlier, CA. Background data was taken from ecoinvent (Ecoinvent, 2016), FEAT (2016), and GaBi 6 (ThinkStep, 2016).

2.2.1. Tomato pomace distribution

The processing of tomatoes for the production of tomato paste results in a residue of 4% mass as tomato pomace (77% Moisture content, Fresh weight basis) (Del Valle et al., 2006). It was assumed that tomato pomace used as cattle feed and as a substrate for biosolarization was distributed wet from the processing facility. The pomace was distributed from 19 identified locations (Table 2), to a dairy farm assumed to be in Tulare County, CA, or an eggplant grower in Fresno County, CA. The distance from each of the 19 processing plants was calculated using the shortest distance (Table 2).

2.2.2. Alternative feed for cattle

To find a nutritionally similar substitute for the tomato pomace in dairy rations, popular dairy feedstuffs were identified through an extension survey (Silva-del-Río et al., 2010) of feeding management practices on 120 California dairies. The average nutrient composition of tomato pomace along with the four most popular by-products used in dairy rations (almond hulls, canola pellets, flaked corn grain, and whole cottonseeds) and the four most popular forages (alfalfa hay, corn silage, oat hay, and wheat straw) were evaluated using the University of California Cooperative Extension feed composition library (Beef Magazine, 2010). Linear programming was used to find the optimal linear combination of the eight potential substitute feedstuffs that best matched the nutrient composition of tomato pomace for net energy of lactation, crude protein, neutral detergent fiber and fat by minimizing the least squared differences of the four parameters. The optimized solution found was cottonseed (whole, with lint), canola pellets and wheat straw at a 46:24:30 mass ratio (<10% water on fresh weight basis). Assumptions for production of the alternate feeds were: (i) cottonseeds from San Joaquin Valley, CA (347 km) (CCCCGA, 2016); (ii) canola pellets from American Falls, Idaho (1421 km), (Capital press, 2016); and (iii) wheat straw from Fresno County (62 km) (USDA, 2015a,b). Transportation from production location to utilization as feed location was assumed to be by truck.

2.2.3. Eggplant establishment

The assumed location for eggplant establishment was Fresno County, CA, in the San Joaquin Valley. Eggplant is grown in plots with a row width of 1 m, and 1 m spacing (50% land utilization).

2.2.4. Agricultural field operations

Common processes for field operations in all pest management options included ploughing, roller, list and shape, tarping and plastic sheeting removal (Table 3). It was assumed that for all agricultural processes a 100-horse power (hp) tractor was used with fuel consumption estimated using the Flash Environmental Assessment Tool (FEAT, 2016). The data used for modelling solarization and biosolarization were obtained from field and laboratory trials performed in UC Davis and supplemented with data from literature (Table 3).

2.2.4.1. Solarization. For the solarization scenario, additional processes modelled to Section 2.2.4 were irrigation and solarization. The solarization timeline was ploughing, one week later levelling and three days later bed listing. After one week a plastic sheeting is laid, and drip irrigation is used throughout the solarization process, with an associated fuel consumption (Table 3). The plastic sheeting is removed and disposed of approximately four weeks later. Solarization GWP emissions are negligible for soils that have low organic matter content or stabile forms of organic matter, such as mature compost (Simmons et al., 2013).

2.2.4.2. Biosolarization. For the biosolarization scenario, additional processes modelled to Section 2.2.4 were pomace spreading, irrigation and biosolarization. The timeline for biosolarization is immediate ploughing of land and spreading of pomace. Levelling is carried out one week later and three days subsequent to that bed listing would be completed. One week later the plastic sheeting is laid with drip irrigation and used throughout the biosolarization process, with an associated fuel consumption (Table 3). For biosolarization, pomace application was 123.8 t ha^{-1} (fresh weight). Pomace is only applied to the beds (1 m) and not the margins (1 m), therefore the application rate modelled was 61.9 t ha^{-1} (fresh weight). The assumed application rate results in 6282 ha of land required ($388,856 \text{ t yr}^{-1}$ at 61.9 t ha^{-1}). Approximately four weeks

Table 3

Life cycle inventory for agricultural operations Life cycle inventory for agricultural operations (per hectare).

	Option 1	Option 2	Option 3
Pomace applied (kg)^a	—	—	61,900
Fumigant applied (kg)	112	—	—
Herbicide applied (kg active ingredient)	0.2	—	—
Plastic sheeting consumed (t)	1	0.7	0.7
Fuel consumed (L)			
Spreading	—	—	30.2
Plough	25.3	25.3	25.3
Level	29.9	29.9	29.9
Plastic sheeting laying	15.15	15.15	15.15
Irrigation	—	201.65	201.65
Plastic sheeting removal	15.15	15.15	15.15
Emissions during soil inactivation (kg CO₂)	—	Negligible	340.5 (biotic)
Plastic sheeting disposal (t)	1	0.7	0.7

^a Fresh weight.

later, the tarp is removed for disposal. Biosolarization emissions are estimated to be 5.5 mg CO₂ per g of wet pomace applied based on prior work that measured emissions from soil amended with tomato pomace under the anaerobic conditions associated with biosolarization (Achmon et al., 2016), although they were not included in this study as they are biogenic (Manfredi et al., 2011).

2.2.4.3. Pesticide application. The pesticide application process was modelled. The timeline for pesticide application was ploughing, one week later levelling and three days later bed listing. After one week plastic sheeting is laid, and fumigant and herbicide application takes place. The plastic sheeting is removed and disposed of approximately 3 days later. LCI data for pesticide application included the processes fumigant and herbicide application and were taken from literature (FEAT, 2016). For each of these processes the fuel consumption and associated emissions were calculated. The fumigant (Tellone II) application rate modelled was 62.5 l (112 kg) per hectare, considering margins. Herbicide was modelled at a rate of 0.2 kg of active ingredient per hectare or 46.9 l of spray solution per hectare, considering margins. Data (Table 3) for the production of fumigant was estimated (FEAT, 2016; FAO, 2015; Ecoinvent, 2016). The production impact of herbicide was taken from FEAT (2016) and averaged from four studies. Herbicide and pesticide parameters were tested in the sensitivity analysis. Fumigant and herbicide application emissions relating to GWP were assumed to be zero.

2.2.5. Plastic sheeting production and disposal

The plastic sheeting (polyethylene) was assumed to be produced in Point Comfort, Texas, (2787 km) and transported by rail. LCI data for plastic sheeting production was taken from Ecoinvent 3.1 (Ecoinvent, 2016). The disposal of plastic sheeting waste was assumed to be in landfill in the closest facility to Fresno County located in Kerman (City of Fresno (2016)) approximately 118 km away. Specific data for landfilling of was taken from Ecoinvent 3.1.

2.2.6. Energy production

LCI data for energy (US specific, average grid mix) and fuel (diesel) were taken from the GaBi 6 database (Thinkstep, 2016).

2.2.7. Transport

For the transport of pomace (wet), fumigant, alternative feed and waste material, a diesel driven, US, semi-truck with a payload of 14–16 t was assumed, with data taken from GaBi 6 (Thinkstep, 2016). The transport processes were modelled to have full capacity and travel 90% on interstate and 10% on rural roads. For the transport of plastic sheeting and herbicide prior to use, diesel rail

transportation was assumed and LCI data was taken from GaBi 6 (Thinkstep, 2016).

3. Results

The results presented are consistent with the system defined in the study scope and include analysis of environmental impact, contribution analysis and sensitivity analysis as per ISO 14040 (2006).

3.1. Life cycle impact assessment

3.1.1. Analysis per environmental impact

The option with the lowest GWP impact (64 kg CO₂-e) per FU was Option 2 (Fig. 4), the use of solarization for soil pest inactivation and feed demand met by tomato pomace utilization. This was followed by Option 3, biosolarization and an alternate feed of cottonseed, canola pellets and wheat straw, which had a total GWP impact per functional unit of 78 kg CO₂-e. This was an increase of 14 kg of CO₂-e over Option 2, per tonne of pomace. Both alternate options resulted in cumulatively lower impacts than BaU, Option 1, which had a GWP of 98 kg CO₂-e (53% greater than Option 2 and

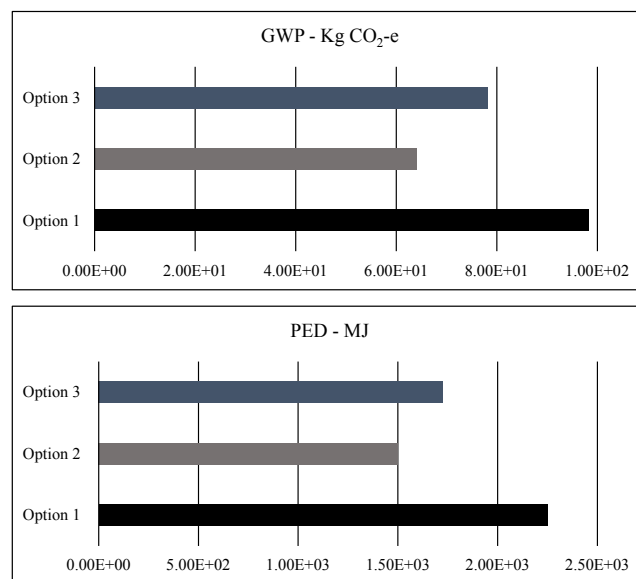


Fig. 4. Total impact for options 1–3 for global warming potential (GWP) and primary energy demand (PED).

26% greater than Option 3).

For PED (Fig. 4), Option 2 resulted in the lowest impact at 1502 MJ per FU. This was followed by Option 3 at 1727 MJ, an increase of 225 MJ per FU. As with GWP, both alternate options (2 and 3), resulted in a cumulatively lower PED than BaU at 2250 MJ per FU. For PED BaU was 50% greater than Option 2 and 30% greater than Option 3.

There was a correlation between the results of the GWP and PED analysis per FU (Fig. 4). For both GWP and PED, Option 2 resulted in the lowest impact, followed by Option 3 with BaU, Option 1, the least favorable option. For Option 3, if biogenic carbon were included for the biosolarization process, the total GWP per FU would be 84 kg CO₂-e. This would not change the ranking for GWP, but would reduce the difference (14.5 kg CO₂-e difference rather than 20 kg CO₂-e) between Option 1 and Option 3.

3.1.2. Contribution analysis

For Option 1, the most significant processes contributing to GWP (Fig. 5) and PED (Fig. 6) were the production of fumigant (37.7% for GWP and 25.1% for PED) and the production of plastic sheeting (31.6% for GWP and 54.4% for PED). For Option 2, the most significant processes contributing to GWP (Fig. 5) and PED (Fig. 6) were the production of plastic sheeting (33.9% for GWP and 57% for PED), the transport of pomace for feed (33.8% for GWP and 22.6% for PED), and fuel consumed during irrigation (20.2% for GWP and 12.6% for PED). For Option 3, the most significant processes contributing to GWP (Fig. 5) and PED (Fig. 6) were, production of plastic sheeting (25.8% for GWP and 49.6% for PED), fuel consumed during irrigation (15.6% for GWP and 10.1% for PED), transportation of alternate feed (20% for GWP and 14.2% for PED) and distribution of pomace (23.2% for GWP and 16.4% for PED).

For Option 1, GWP and PED had different contribution rankings. Fumigant production made the largest contribution to GWP, approximately 6% more than plastic sheeting production, while film production made the largest contribution to PED, approximately 32% more than fumigant production. However, the

contribution rankings were the same for GWP and PED for Options 2 and 3.

3.1.3. Sensitivity analysis

The results of the sensitivity analysis (Fig. 7) showed that parameter sensitivity differed between options. For Option 1 it was seen that the amount of plastic sheeting used and fumigant consumed were the most sensitive at $\pm 3.09\%$ and $\pm 3.8\%$ respectively. For Option 2 the amount of plastic sheeting consumed was most sensitive, $\pm 5.3\%$, followed by feed transport distance, $\pm 3.38\%$. For Option 3 the amount of plastic sheeting consumed was most sensitive, $\pm 4.55\%$, followed by transport distance of tomato as feedstock for biosolarization, $\pm 2.32\%$, and transport distance of alternate feed, $\pm 2.0\%$.

A large amount of secondary data was used for the study but no data gaps were found whilst carrying out a completeness check. The pedigree of data was limited by its availability. Background data was taken from databases, however it was found that some processes using this data, e.g. plastic sheeting production, made a large contribution for all three options and was shown to be sensitive (Fig. 7). As all three options used plastic sheeting, the reduction in impact would not change the result. Fumigant production was also shown to be sensitive, but only affected Option 1. However, it would take a 92% reduction in its CO₂-e impact to change the result, i.e. for it to have a lower impact than Option 3.

4. Discussion

4.1. Interpretation

In California, the diversion of tomato pomace from its current use as cattle feed ingredient to an alternative utilization as a substrate for biosolarization was shown to result in a reduction of GWP and PED, by 20% and 23%, respectively. However, Option 2 was the most favorable option for both GWP and PED. This is because solarization does not require additional material inputs compared to

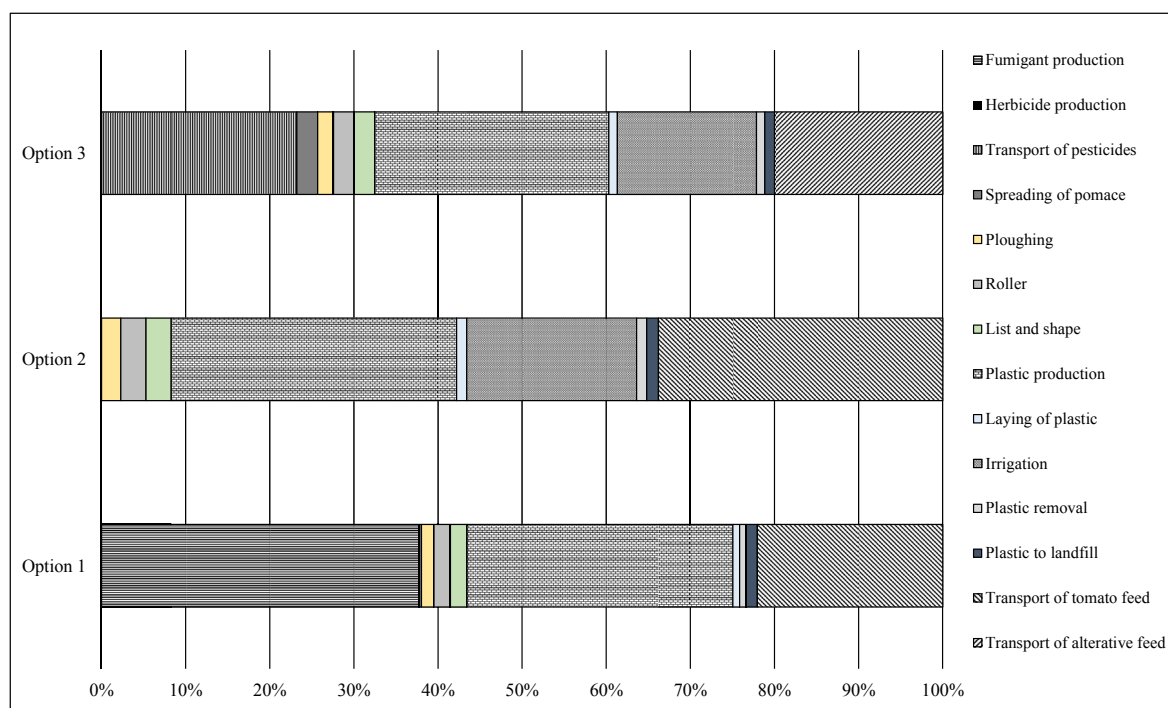


Fig. 5. Contribution analysis for option 1–3 for global warming potential (kg CO₂-e).

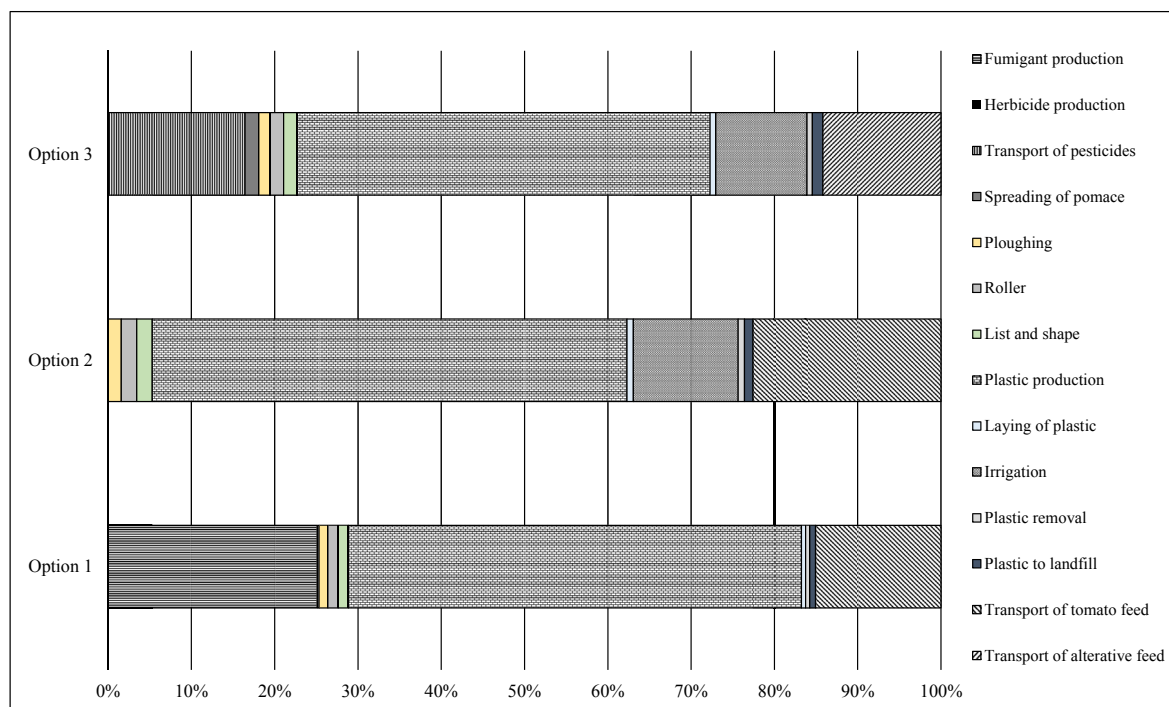


Fig. 6. Contribution analysis for options 1–3 for primary energy demand (MJ).

other pest management options (pomace for biosolarization and fumigant and herbicide production for BaU). These materials were responsible for a large amount of the estimated impact, 37.1 kg CO₂-e and 667 MJ per FU (fumigant and herbicide production) for Option 1 and 18.18 kg CO₂-e and 145 MJ per FU for Option 3 (transport of pomace for biosolarization). This study did not incorporate the efficiency of the pest management technologies. Differences in their ability to control various pests in the soil and subsequent effects on crop yields could influence selection of the pest control technology. This is particularly true for solarization where pest inactivation can be incomplete due to heavy reliance on the local climate and weather (Stapleton, 2000). Future LCAs should consider potential variability in efficacy for competing pest management strategies.

The focus of this case study was California. If the potential reduction shown between Option 1 and Option 3 was taken for the reference flow (388,856 t fresh weight pomace), a hypothetical total reduction of 7.7 M kg CO₂-e and 203,000 GJ could be achieved. However, it should be noted that biosolarization for eggplant production alone would not consume the entirety of the seasonal pomace flow. The reference flow could be used to biosolarize 6282 ha of land under the assumed amendment conditions; however, the most recent statistics indicate that only 567 ha of eggplant were cultivated in 2001. As a result, additional crop targets that are equally amenable to biosolarization should be considered in future LCA studies.

4.2. Biogenic carbon

The results of this study did not include biogenic carbon. Its inclusion would change the GWP of Option 3—84 kg CO₂-e per FU, an increase of 5.5 kg CO₂-e per FU. The inclusion or exclusion of biogenic carbon has been discussed (Guinée et al., 2009; Levasseur et al., 2013) but no agreement has been reached in the context of LCA. It can be surmised that when a study may be used to stimulate the bioeconomy it is important that the study is robust (Guinée

et al., 2009), and not including biogenic carbon could distort the results (Levasseur et al., 2013). Therefore, presenting the results with the inclusion and exclusion of biogenic carbon and how it affects the results is most appropriate. In the case of this study, biogenic carbon did not distort the results.

4.3. The bioeconomy and waste valorization

The bioeconomy has been valued at \$1.25 trillion in the US (Batchelor, 2012) and \$2.3 trillion in Europe (EC, 2010). The motivation to engage in the bioeconomy is twofold: (i) the reduction of greenhouse gases; and (ii) the change from fossil-based to renewable feedstock's (Teagasc, 2008). Biomass is acknowledged as a sustainable alternative to fossil sources, characterized as having a low carbon footprint. As was shown in this study the use of a biomass substrate, tomato pomace, for biosolarization resulted in a lower carbon impact than BaU. To fully assess the whole supply chain, the use of LCA ensures that if impacts are shifted elsewhere, be that upstream or downstream, this is captured. Challenges exist to the expansion of the bioeconomy, as the transformations of wastes/residues to a productive use as a substrate rely on those wastes/residues being produced using fossil sources. In order to reduce this reliance, synergies must be identified between and within systems. In this study the use of a crop by-product, tomato pomace, to be utilized for another crop, eggplant, was shown to be environmentally beneficial.

4.4. Benchmarking biosolarization in California

This baseline LCA serves as a benchmark to consider how best to reduce impacts for biosolarization in CA. For this case study, the co-location of food production and processing systems would further reduce carbon and energy impacts and accelerate the development of a circular bioeconomy. Such approaches have been shown to be feasible and environmentally sustainable in other situations such as eco-industry parks relying on industrial symbiosis. As a result,

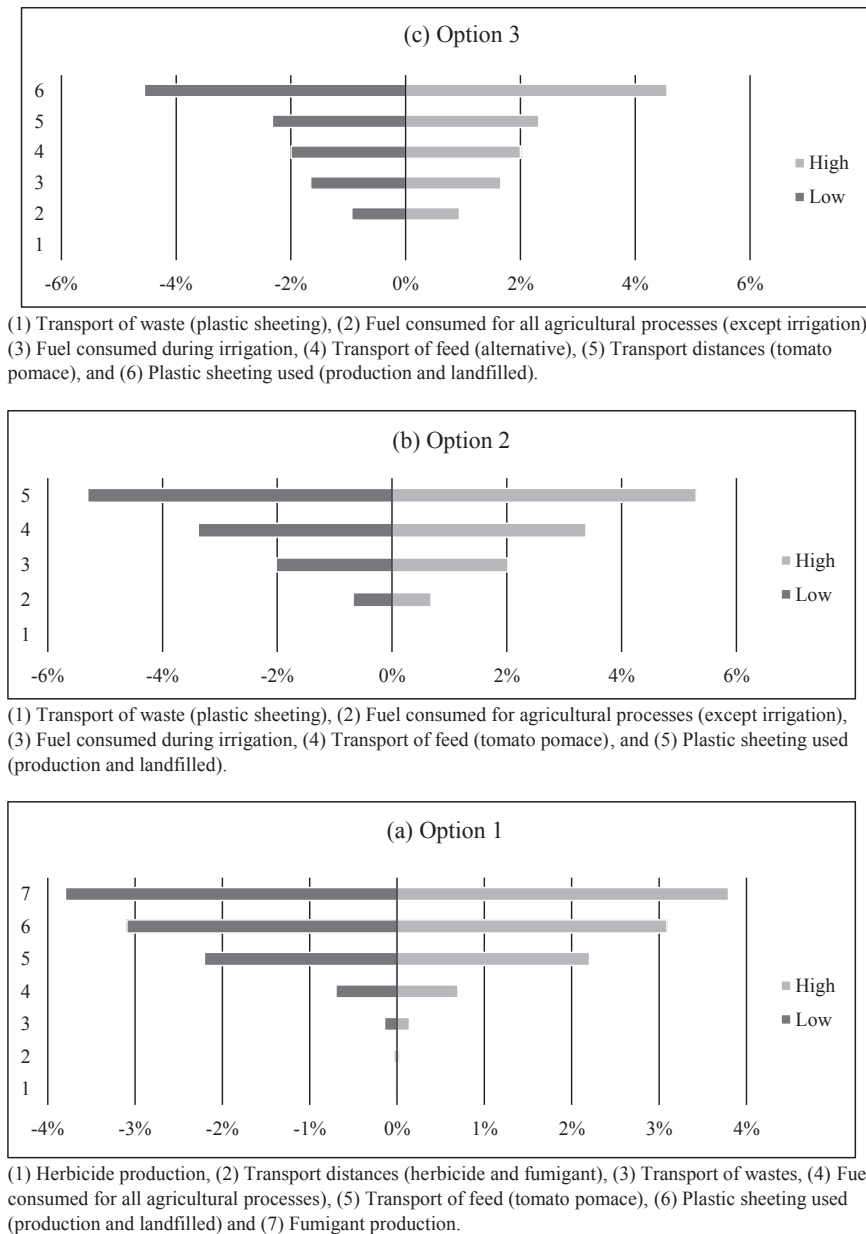


Fig. 7. Sensitivity analysis for Option 1 (a) Option 2 (b) and Option 3 (c) for global warming potential (kg CO₂-e): processes changed $\pm 10\%$.

considering additional biosolarization sites proximal to each tomato processing facility may reveal additional impact reductions. This study assumed that plastic sheeting used during all three alternatives would be sent to landfill, which is the common management approach in the tomato sector in California (CIWMB, 2008). Plastic sheeting waste disposal was not found to be a hot-spot, but its production was important. Therefore, if closed loop plastic sheeting recycling was feasible, which is in line with circular economy principles, there is the potential for a reduction in the environmental impact and thus should be included in future research goals, and considered in future studies of solarization/biosolarization. It was also assumed that the tomato pomace used as feed would be distributed to Tulare County. If sufficient cattle were present in Fresno County for consumption of the tomato pomace, a reduction of 3.52 kg CO₂-e and 55 MJ per FU could potentially be saved. However this is based on an assumed average distance. In order to fully exploit the potential environmental and

economic saving, transport optimization would also be necessary.

4.5. Future biosolarization research

Future LCAs of biosolarization should include additional environmental impacts such as eco-toxicity potential and human-toxicity potential as these relate to pesticide use (Margni et al., 2002) and a water use indicator related to irrigation (Hoekstra et al., 2011). The use of a downstream functional unit for valorization technologies is recommended; such as pest suppression per m² that includes an assessment of the efficiency of biosolarization versus its alternatives (solarization and chemical pesticides) should be considered.

In order to make biosolarization more attractive as an alternative to fumigation in the bioeconomy, future research should include: (i) the use of an alternative material to plastic with a lower environmental impact; (ii) the optimization of water usage during

irrigation, which is a particular barrier for California due to water stress; and (iii) feasibility of co-location of crop and processing systems. However, it was found that the majority of the impacts were shown to be outside of the tomato processors' immediate control, and as such the diversion of tomato pomace to biosolarization must be encouraged.

5. Conclusion

The utilization of tomato pomace for biosolarization in California, in the context of soil fumigation prior to eggplant crop establishment rather than as a component of animal feed was seen to be environmentally beneficial from a global warming impact and energy conservation perspective when compared to business as usual. However, solarization was found to be a better option due to its reduced resource input but this LCA did not incorporate the efficiency of the pest management technologies. Future LCAs of waste valorization for pest control should consider using a qualitative downstream functional unit. To increase the appeal of biosolarization in the circular bioeconomy, fuel consumption during irrigation and plastic sheeting use during the biosolarization process need further research to identify how best to reduce their contribution to environmental impact. Further environmental reductions may be possible by crop synergy co-location. Further studies must consider water consumption, eco-toxicity potential, and human-toxicity potential.

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