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Enhancement of sustainable bioenergy production by valorising tomato residues: A GIS-based model

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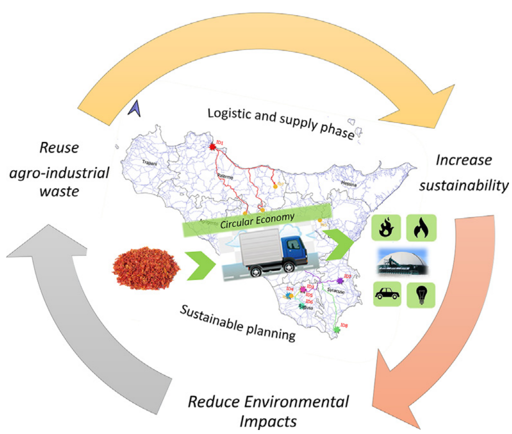
HIGHLIGHTS

- Network information technologies were adopted for developing strategic planning.
- Tomato peels valorisation was investigated based on their territorial availability.
- Logistics and supply phases were considered for minimising environmental impacts.
- Operational GIS-model for defining sustainable strategies was carried out.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to increase the utilization of renewable energy sources, the biomethane production through anaerobic digestion has notably developed over the last years. Although, it is worldwide recognized, that valorising waste resources (i.e., by-products) is an opportunity to improve the efficiency rate of the agro-industrial chains, by reducing economic and environmental impact, it is necessary to support the strategic planning development of a future sustainable biomethane chain in line to circular economy. In this study, by adopting network information technologies, the importance of a strategic planning for sustainable developing biomethane sector was highlighted, since feedstocks logistic and supply phase is a key-aspect of any bioenergy project. The developed Geographic Information Systems (GIS) – methodology, that could be applied in any territorial area considering any type of biomass, allowed to define suitable locations for allocating new anaerobic digestion plants with the aim of developing a sustainable valorisation of tomato residues, by minimising the economic and environmental impacts.

The achieved results provided advanced knowledge for the literature on the topic, helping to develop an operational GIS-tool for defining sustainable strategies for planning new plants, and proved that the development of integrated approach to define sustainable strategies for resource management along the whole supply chain is crucial.

1. Introduction

Nowadays, the circular economy is one of the main orientations for reorganizing a strategical economy of sustainable development (Valenzuela and Böhm, 2017). The circular economy represents an innovative approach

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to sustainable development (Independent Group of Scientists appointed by the Secretary-General, 2019) and is therefore the focus of attention among policymakers who have integrated circular economy commitments in their national development goals and climate programs to shape linear economy.

Furthermore, this approach has been accelerated by the COVID-19 pandemic crisis. Indeed, critical issues related to the vulnerability and underlying constraints of existing linear supply chains emerged during this state of emergency (Hofstetter et al., 2021). In particular, the most well-known criticalities of the linear economy that relies on overconsumption and underutilization have emerged: atavistic dependence on raw materials that do not have unlimited access, employment insecurity, and poor working conditions (Sooriyaarachchi et al., 2015; Dvořák et al., 2017).

Currently, the fossil fuels dominate the global energy chain with a production of about 500 EJ per year, and biomass contributes to this rate for about 10 %, making it by far the most significant Renewable Energy Sources (RES) (Dornburg et al., 2010). Residual biomasses obtained by agro-industrial processes and energy crops represent a concrete feedstock for biofuels generation, mainly due to their widespread diffusion in all the territorial network and their low cost (Selvaggi et al., 2021a; Monlau et al., 2015; Zhao et al., 2017). In detail, biomass coming from agro-industrial chains is seen as one of the most dominant future RES able to combine the concepts of bioeconomy and circular economy (Selvaggi and Valenti, 2021). Agro-industrial residual biomasses are obtained by biological process and if used for the anaerobic digestion system can be converted into green and renewable energy: biogas for the electrical generation or biomethane for the gas grid (Murano et al., 2021).

Sustainable bioenergy chains require optimization of the structure and operation of the involved network and of supply chain, by considering economic, environmental, and social aspects, adapted to the specific conditions of the respective production system (topology and climate, seasonality, technologies, end application) (Gold and Seuring, 2011; Vitale et al., 2022). Moreover, the lower energy density score of most agro-industrial by-products (in comparison with fossil fuels) makes their handling, storage, and transportation more costly per unit of energy carried (Allen et al., 1998). As confirmed by Schnorf et al. (2021), the principal barrier to biomasses logistic chain is their transportation cost and not their energetical and environmental characteristics. Maximum travel distances are highly variable and are strongly dependent on the logistic solution adopted (Capponi et al., 2012). Because of the complex trade-offs involved, the various design decisions of competing supply chain networks cannot be made stand-alone (Balaman and Selim, 2014).

In this regard, as stated by Mula et al. (2010), a supply chain can be considered as an integrated process in which suppliers, producers, distributors, and retailers, work together to acquire raw materials with a view to reuse them by their conversion into end products which they distribute to retailers. Given the globalization of operations, new models and tools for improving the forecasting, replenishment and production plans along supply chains are required (Mula et al., 2010). Furthermore, within the context of supply chains, the integration between production and transport planning is needed, in order to simultaneously optimize both these processes, since transport represents a service that is essential for the functioning and growth of worldwide economy (European Commission, 2010).

The location for planning new plants should be evaluated according to a case-by-case approach. It is desirable to realize biomass energy plants as close as possible to feedstock availability sites, without bearing others economic and environmental impacts of transporting biomass streams (De Meyer et al., 2014). The reduction of the distances between the locations where biomasses are generated and the plants where the same biomasses are used to be converted into bioenergy contributes to improve the value of the global waste-to-energy project (Gonzales et al., 2013).

It is worldwide known that due to seasonal variations, spatial dispersion, low density, and other biomass resource characteristics, logistics costs account for approximately 50 % of the total cost (Cao et al., 2021). As result, logistics system optimization research is of utmost importance to the development of biomass resources. In this regard, several research works in literature addressed this topic, but almost all only with the main aim of minimising total costs. Cao et al. (2021) highlighted this gap in literature by showing that no research articles addressed any proposal that can simultaneously optimize transport and production planning beyond considering the costs and capacities associated with a limited transport resource. Furthermore, they (Cao et al., 2021) highlighted the necessity of developing optimization models and tools for the supply chain production as well as transport planning processes with the application of tailored new planning models to real case studies. In their studies Ranjbari et al. (2022a, 2022b), proposed systematic reviews of the most important scientific paper focused on the biomass and organic waste, and on biofuel supply chain management with a circular bioeconomy perspective. As main findings it was found that academia has recently focused on seven emergent research areas including the CE implementation in the agricultural sector (Ranjbari et al., 2022b).

Recently, network information technologies have been widely used to support logistics systems. In fact, it is necessary to consider major local specifications that influence the logistics of the supplying the biomass (Mobini et al., 2011). These developing technologies allow logistics system to perform as both a creator of social value, a competitive lever, and an enabler of sustainability (Tang and Veelenturf, 2019). Among them, the Geographic Information Systems (GIS) technology can highlight both advantages and disadvantages of each domain and its potential, visualizing the spatial data (Srisawat et al., 2017). Accordingly, the information system controlled by it allows the modelling of complicated conditions through large data sets and data interactions (Guerlain et al., 2016). Powerful data management, spatial analysis and decision-making capabilities make the GIS technologies a successful tool for logistics location analysis (Xie, 2018). In this regard, minimising impacts is always one of the most important aims for logistics service suppliers (Ehmke et al., 2018). About feedstock supply chain and logistics, GIS tools have also been applied to support decision making process and to encourage new biogas production plants at local or national levels (Valenti et al., 2018) by developing win-win solutions.

With this in mind, this research focused on the importance of a strategic planning for sustainable developing biomethane sector by adopting network information technologies to evaluate suitable areas for allocating new anaerobic digestion plants. Therefore, by adopting a GIS based model, this study investigated the Sicilian tomato chain to estimate the sustainability of the by-products obtained after the agro-industrial process of production sauce by fresh tomatoes, since the whole Mediterranean area is largely characterized by tomato production and processing (Ingrao et al., 2019), with just under 38 million tons of tomatoes processed yearly (WPTC, 2018) and consequently large amount of tomato residues that could be re-used according to circular strategical models.

By considering the network of feedstock collection points, plants, and storage units, the location of a bioenergy plant is influenced by several environmental, economic and social factors that are essentials to determine the number, location, and dimension of bioenergy facilities, which play an essential role within the biomass energy supply chain. To find the optimal locations for bioenergy plants, several studies used an integrated GIS and Multi Criteria Analysis (MCA) tools. One of the most applied MCA is the Analytical Hierarchy Process (AHP), based on outranking techniques. This methodology is able to contemporary estimate several factors, giving them a different weight, depending on the impact decisions (Wood et al., 2018; Sahoo et al., 2016).

By following the results achieved by Cao et al. (2021), with the main purpose to fill the gap in the literature related to the development and application of tailored new planning models to real case studies, the main aim of this work was a critical analysis on the current existing biogas plants network, within a chosen study area, by demonstrating that they do not allow a sustainable use of tomato peels, due to their location. Then, after to demonstrate the need to locate new plants, according to a novel GIS-based model here developed, new areas were investigated for allocating suitable anaerobic digestion plants for producing biomethane, with the purpose of developing a sustainable valorisation of tomato residues. New potential areas, and not detailed localization, have been identified by proximity, or by minimising transport.

Fig. 1. The study area in the Mediterranean basin: Sicily region (Italy).

In fact, the purpose is to simulate shortest roads to collect these by-products: it will be minimised both economic and environmental impacts for long-distance transport of bulky feedstocks and energy will be obtained from the closest sites where the by-products are highly available, such as tomato industries. The transport costs could be estimated as fuel consumption for the kilometre, however in this study most emphasize taken the environmental and social impact generated by a localization outsides certain radius km.

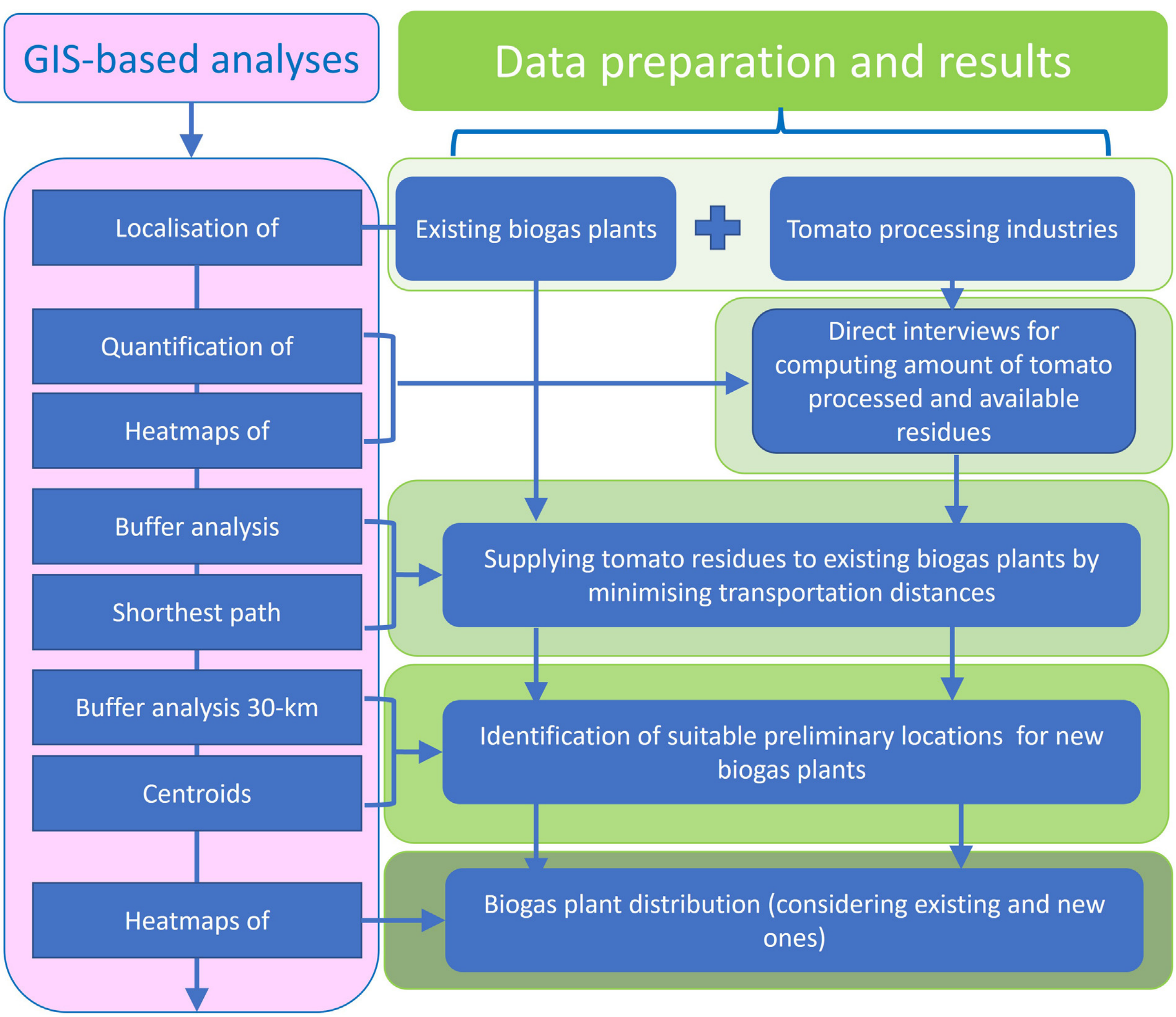

Fig. 2. Methodology flow chart.

The development of a more integrated roadmap to manage the resources is essential to implement sustainable approach and to promote strategies along the whole supply chain in order to valorise by-products maximising the ratio bioenergy/feedstock (Lin et al., 2013). Nowadays, no research studies were found in literature that evaluate the sustainability, in terms of analysing logistic and supply phase, of using by-products for biomethane production trough anaerobic digestion, prior real using them.

Therefore, in order to fill this gap, a GIS model based on cartographic approach was developed with the aim of by taking into account the reduction of km-distances, the minimizations of transportation impacts, and therefore GHG emissions. The developed model can be applied for every feedstock chain in every region. For its application, due the importance of the Mediterranean tomato industry, this study aims at fill gaps in knowledge of the potential energetical yield of the by-products obtained by tomato processing industries as useful feedstocks for biogas plant in areas where the biomethane sector is still uncommon. By providing for the use of residual biomass in biogas plants not far from the sites of their production, a reduction in GHG emissions related to the logistic system of biomass transport but also a reduction in land consumption related to the non-cultivation of energy crops would be achieved. Theses aims could be relevant for planning the sustainable development of the biomethane chain and the developed model could be applied to whatever by-product or agro-industrial waste. The obtained results show the localization of territorial areas highly characterized by the availability of this type of by-product. This approach should be the basis of future development policies. Therefore, decision makers should consider where biomass is most available to feed future biogas plants before planning new actions to develop the biomethane sector.

2. Materials and methods

In this study, with the aim of investigating the possibility of using tomato residues as suitable feedstock for producing biogas and biomethane, a tailored methodology, based on GIS, was developed. In detail, statistical tools were adopted and combined to the GIS analyses for developing the GIS-based model, by a two-step approach (including survey and GIS-based analyses).

Biomass data such as the biomass amount, the location of tomato processing industries and the existing biogas plant were collected by a survey, then organized and elaborated. GIS-based analyses were then carried out on the combined data to assess the locations of the already existing anaerobic digestion plants and determine both the suitable locations and collection areas for new similar plants.

Biomass type and quality highly influence the selection of handling equipment due to the lowest impact in terms of economic and environmental aspects. Indeed, generally, biomass with lower water content allows transporting more mass of material per unit distance.

In this regard, in the study area, truck transportation on road is generally well developed, and is usually the unique or most economical mode of transportation (railway is not efficient in all the region and far from the plants considered in this study) but becomes expensive as travel distance increases.

2.1. Study area

The Sicily, one of the 20 regions of Italy subdivided into 9 provinces, is known as the Mediterranean largest island, with about 26,000 km^2 of covering surface. It is in Southern Italy, bordering on Tyrrhenian Sea to the North, Ionian Sea to the East, and Mediterranean Sea on the other coasts (Fig. 1).

More than 62 % of the Sicilian territory is hilly, 24 % is covered by mountains, whereas the last 14 % is flatland (i.e., the Catania Plain and the Gela Plain). Over the time agriculture has been, and it is still now, the most important economic resources of Sicily, due to the quality and wide variety of productions. Regarding the climate pattern, it is typically characterized by mild/wet winter and hot/dry summer. This unique climate pattern combined with the large agricultural land area (i.e., Sicily has the largest Utilized Agricultural Area (UAA), equal to over 1.387 million ha which correspond to 10.8 % of the national UAA (EBA, 2021)), make this

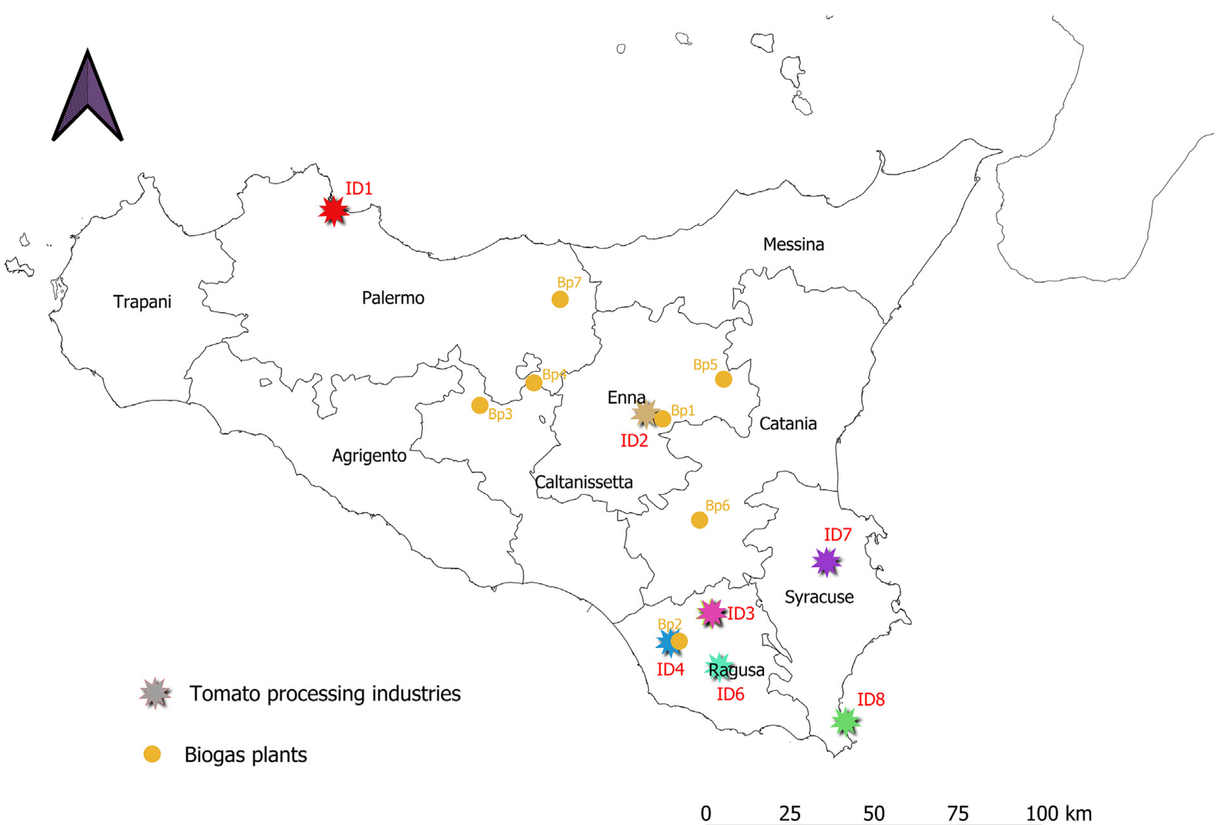

Fig. 3. Geographical distribution of biogas plants and tomato processing industries.

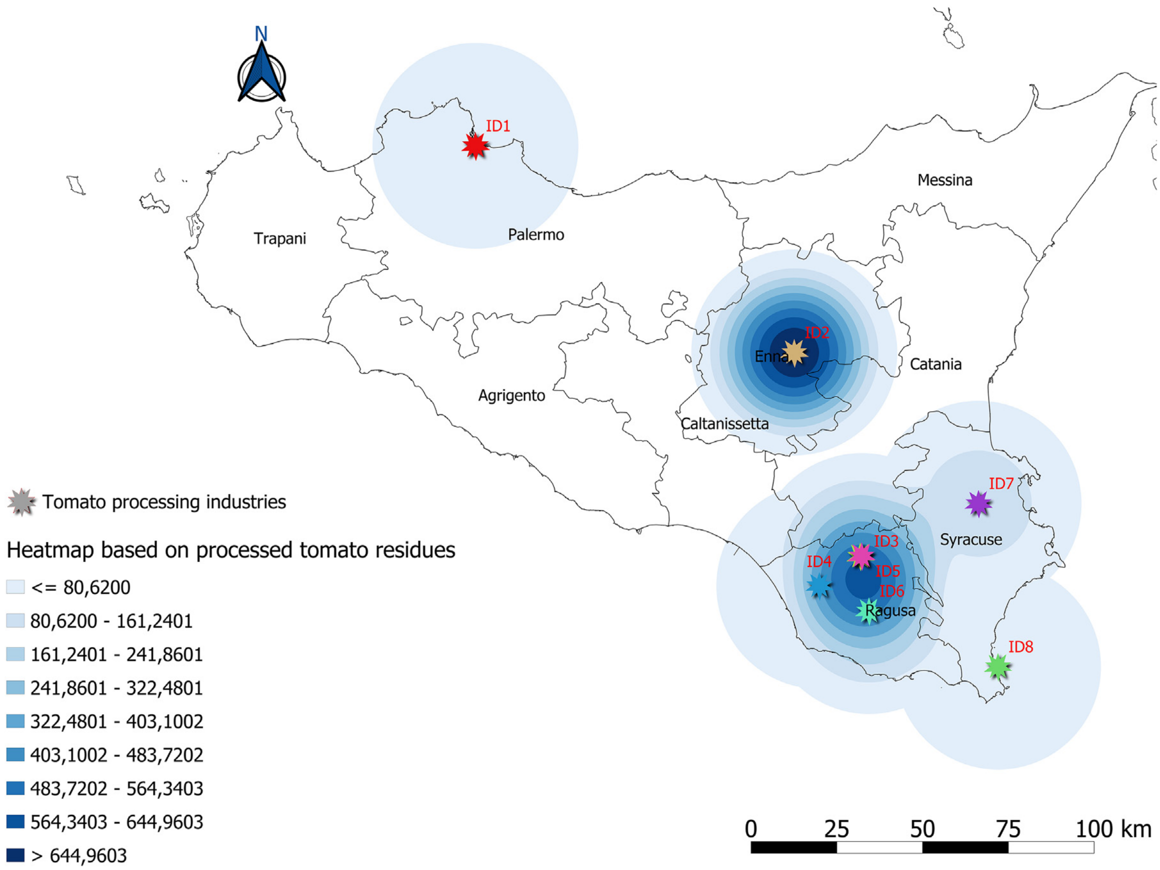

Fig. 4. Heatmap based on the amount of processed tomato residues.

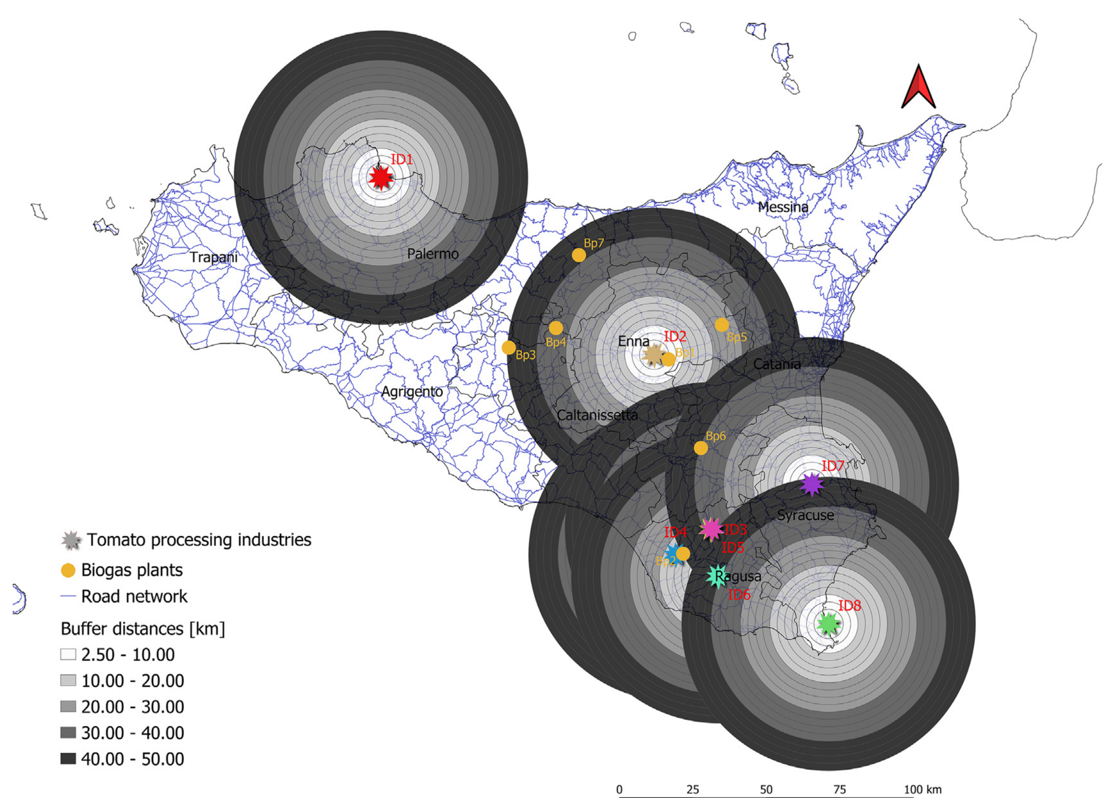

Fig. 5. Graphical output of the multi-distance buffer analysis.

region a suitable area with a great potential for bioenergy production (i.e., solar energy, wind energy), creating favourable conditions for developing technical solutions also aimed at increasing the sustainable development for biogas/biomethane sector, thus it was selected as study area.

Furthermore, in Sicily, more than about 4 million metric tons of biomass are yearly produced by agro-industrial activities and therefore are available and potentially reusable for biogas production (Valenti et al., 2018). As in whole Mediterranean area, biomasses include by-products from the agro-industrial chains that represent more than 60 % of the total produced biomasses (i.e., tomato peels, citrus pulp, olive pomace, and whey), agricultural crop residues (i.e., field residues and process residues), and wastes from livestock farming (mainly beef and dairy cattle), are highly available to produce renewable energy from anaerobic digestion process (Valenti et al., 2018). The horticultural sector is an essential production chain for the agricultural economy of the region. Within this sector, Sicily occupies an important place in Italy, both in terms of production volumes and cultivated area (Selvaggi et al., 2021b). The most productive horticultural greenhouses species are, in order, tomato, zucchini, eggplant, bell pepper, and watermelon, while the most productive horticultural open field crops species are, in order: tomato, melon, artichoke, cauliflower, and lettuce. Then, considering Italian tomato production of about 92,000 ha, Sicily is the third largest Italian region in terms of cultivated horticultural open fields area, after Emilia-Romagna and Apulia, with about 12,000 ha (on average from 2016 to 2020). In the same period, Sicily is the largest Italian region in terms of horticultural greenhouses cultivated area (about 3000 ha of the total 7300 ha in Italy) (Selvaggi and Valenti, 2021). Sicilian climate conditions are suitable for this type of crop. Tomato is a warm-season vegetable crop, sensitive to frost and killed by freezing temperatures. For a proper growth of tomatoes, a temperature range between 10 and 30 degrees is required. Plants do not set fruit when night temperatures are consistently below 10 °C and are damaged if temperature exceeds 35 °C. Moreover, this cultivation requires high amounts of potassium and calcium. Tomato crops are rather resistant to salinity and cherry-tomatoes develop a sweeter taste when grown under moderate salinity (Parlato et al., 2020).

2.2. Data analysis

Before carrying out the spatial analyses and develop the GIS-based methodology, in this study an extensive database was developed and implemented based on data from National Institute of Statistics (Istat) (ISTAT—Several YearsAvailable, n.d.).

In detail the steps listed below were followed (Fig. 2):

1. Data preparation for GIS-based analyses: administrative boundaries of Sicily region (Web Map Service), the Regional Technical Map, tomato processing industries and existing biogas plants.
2. GIS-based analyses for carrying out the maps.
3. Localization of both tomato processing industries and existing biogas plants.
4. Quantification of the amount of both tomato processed and tomato residues suitable for valorising into new-added value products (direct interviews of tomato processing industries).
5. Weighted heatmaps of available tomato residues at regional level.
6. Buffer analysis to define acceptable transportation distances, by considering existing infrastructure network, for supplying tomato residues to existing biogas plants.
7. Computation of shortest paths due to logistic and supply phase in order to choose suitable biogas plants for valorising tomato residues by minimising transportation distances.

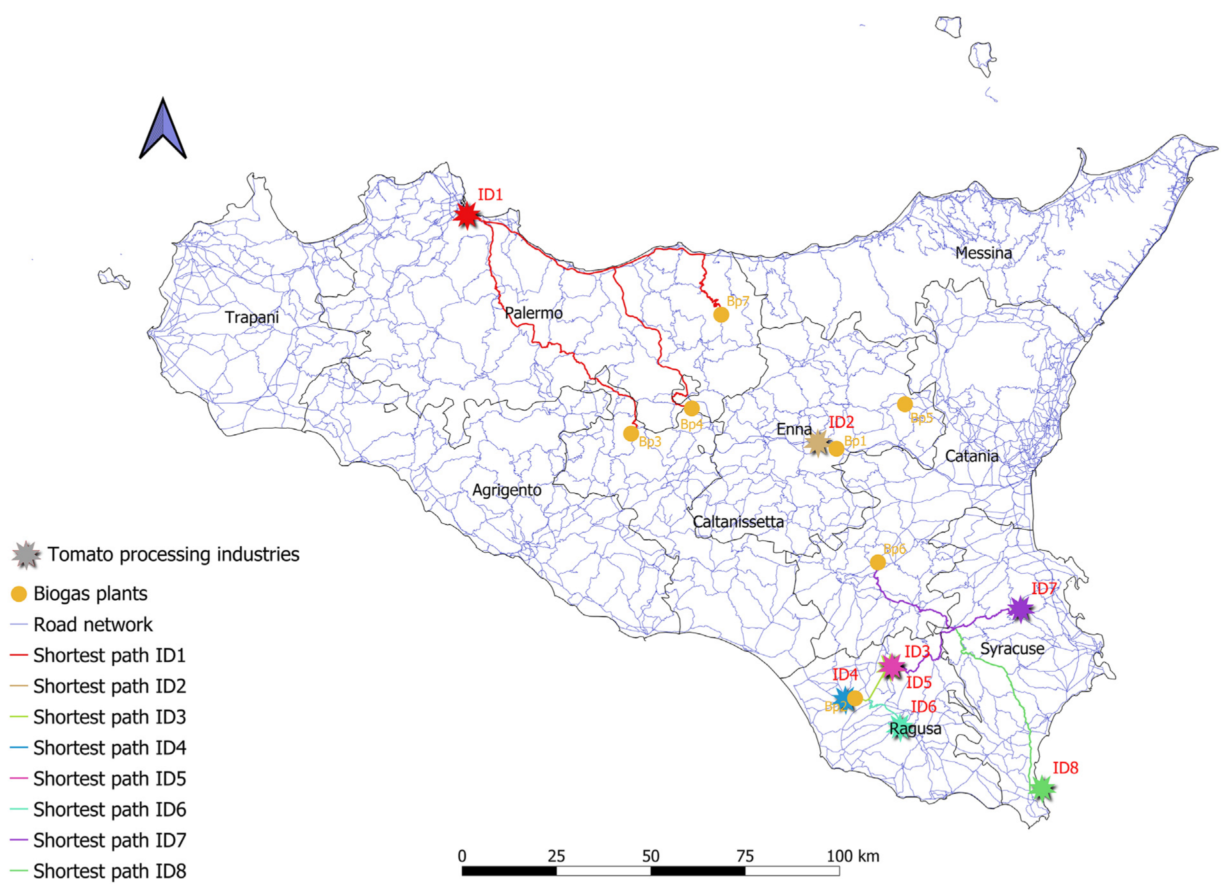

Fig. 6. Road route to connect tomato processing companies to biogas plants.

8. Selection of suitable territorial areas for those tomato processing industries located too far, in terms of kilometres, from the existing biogas plants.
9. Identification of suitable preliminary locations by adopting buffer analysis plug-in (30-km radius set) and centroid plug-in.
10. Heatmap of biogas plant locations distribution (considering both existing and new ones)

Since, as it well known, QGIS software (v.3.10.11) is a significant decision support tool proper to gather, manage, investigate, and localise geographical data, it was used to carry out all the spatial analysis useful for developing GIS-based model. The GIS model based on cartographic approach was developed with the aim of developing a sustainable valorisation of tomato residues, therefore new suitable areas were investigated for allocating suitable biogas/biomethane plants by taking into account the reduction of km-distances, the minimizations of transportation impacts, and overall related GHG emissions. Four different map layers were allocated to the setpoint parameters of tomato processing industries, biogas plants, road networks, and administrative boundaries of Sicily region.

As base map the administrative boundaries of Sicily region provided by the Sicilian region Web Map Service, and the Regional Technical Map (RTM 2008) for producing thematic maps, were used.

In order to estimate the amount of processed tomato, all the main tomato processing industries located in Sicily were identified and analysed within the region and located in GIS, as first target parameters, by using their Global Positioning System (GPS) coordinates. Then, they were interviewed for assessing the quantity of tomato processed and the obtained residual amount that could become a feedstock of the diet for producing biomethane by anaerobic digestion.

In detail, each industry, through a tailored questionnaire, was interviewed to acquire information on their most important structural characteristics, their production goals, and their processed tomato amount and residual products. Acquired data, referred to the time interval 2019–2020, were elaborated in anonymous form, for estimating both the amount of tomato processed residues and their spatial location within the study area.

From these data, after their elaboration, the heatmap of tomato industries based on their amount of tomato residues was carried out for showing the distribution of this kind of by-product, exploitable as new biomass at territorial level.

A second map layer reported the localization of the already biogas plants sited within Sicily, by using their GPS coordinates. Several layers combinations were adopted to produce the target information related to the location and collection area for biogas plants.

Building upon the tomato processed amount and farm location data, collection areas and road network analyses were carried out to evaluate the suitability of the already existing biogas plants and their corresponding collection boundaries, and, if necessary, new suitable areas were considered for locating new plants. The minimization of the transportation impact was the key criterion to carry-out GIS analyses.

Due to the possibility of generating a multi-distance layer from an input vector layer and a set of distances, the Multi-Distance Buffer plugin tool, available in QGIS software, was used to define the collection boundaries and compute the transportation distances. The tomato processing industries were considered as vector points. Different radius from 2.5 km to 50 km around the vector points were set as buffer zones. The maximum value of 50 km was chosen since for bioenergy plants the transport up to 50 km have a fixed cost per route, instead of, over 50 km they have different rates according to the extra km. This is the ordinary condition in all the study area. Since this research represents a first step for approaching new suitable locations, a sustainable distance, not only in terms of environmental impact (e.g., less kilometres), but also in terms of costs (e.g., keeping low supplying-costs), was set.

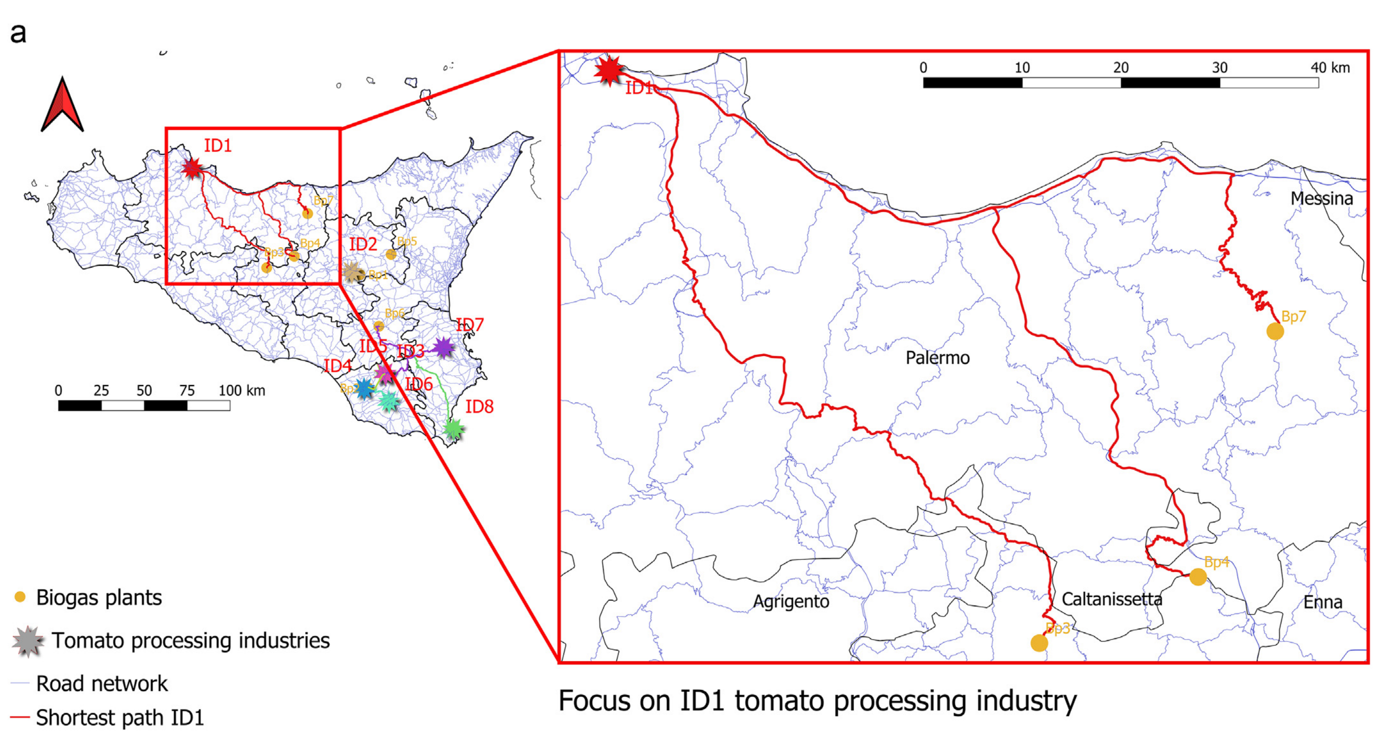

Fig. 7. Focus maps on the tomato processing industries shortest paths. a) Focus on id1 tomato processing industry. b) Focus on ID2 tomato processing industry. c) Focus on ID3, ID4, ID5, and ID6 tomato processing industries. d) Focus on ID7 and ID8 tomato processing industries.

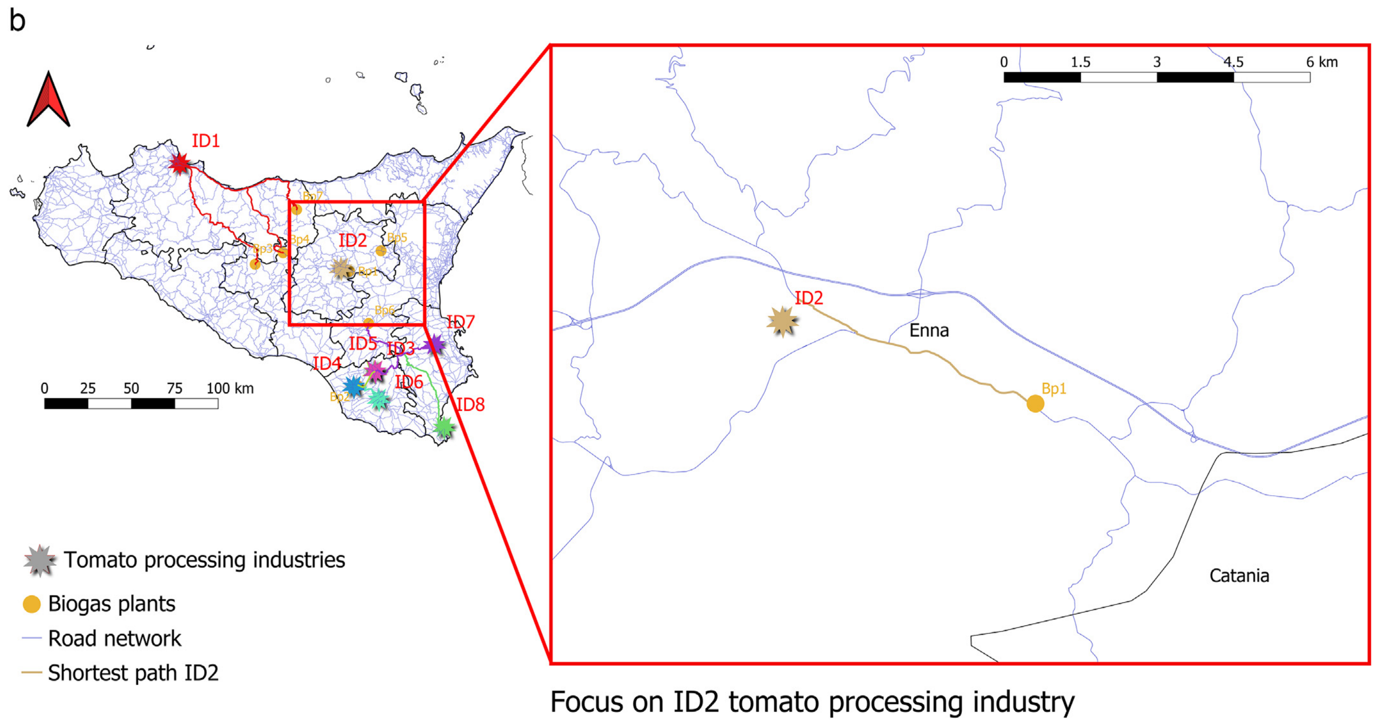

Fig. 7 (*continued*).

The OpenStreetMap database was combined to the RTM 2008 and used to generate the transportation networks. The datasets of highways and primary and secondary roads, the distance from individual tomato processing industry to the biogas plants were computed, by adopting the Road Graph plugin tool, available in QGIS software.

For tomato processing industries that fell into intersecting areas between different buffer zones, the shortest path plugin, available in QGIS software, was used to establish in which biogas plant the tomato processing industries would flow its residues.

As reported in Fig. 2 firstly all tomato processing industries were localised by their GPS coordinates in GIS map and combined with the already existing biogas plants localisation.

Elaborated data were adopted for producing the Heatmap, by using tailored plugins available in QGIS software, based on the amount of processed tomato residues.

In order to deeply analyse the link between tomato processing industries and existing biogas plants with the aim of identifying for each industry the suitable biogas plants for valorising their residues, a map with buffer zones was carried out.

From each tomato processing industry (IDs), by setting 50-km distances, buffer analysis was applied, aimed at defining the boundaries for choosing the suitable biogas plants for valorising tomato residues with the key criterion of minimising transportation impact.

Areas around individual tomato processing industry with a central zone of 10 km radius and the areas with seven incremental 2.5 km radius from 2.5 to 50 km were set to establish the biomass collection boundaries for selecting the tailored biogas plant. For those processing industries in overlapping zones of neighbouring biogas plants, the transportation distances to different biogas plants were computed using the road graph plugin tool. The shortest transportation distance was the fundamental criterion that was adopted for determining which biogas plant should receive tomato residues from the industries in the intersection zones. Then, with the aim of defining the biogas plant for allocating of tomato residues, the road network was considered and the shortest paths from processing industries (IDs) to biogas plants (Bps) were carried out and reported on GIS map.

Therefore, new suitable territorial areas were investigated for reducing km-distances by minimising transportation impacts and overall, the related GHG emissions. In detail, sustainable planning of new biogas plant location was carried out in GIS software. Firstly a 30-km radius buffer zone was conducted from the selected IDs, and overlayed with the base map of Sicily. Then the results of the overly analysis were reported and the suitable areas at provincial level were highlighted.

Next step was focussed on suggesting a suitable location within the selected areas. By focussing on each identified suitable territorial area, firstly, the municipalities were overlaid with the 30 km-distance buffer zone, then by adopting Polygons Centroid tool available in QGIS, the centre of the selected buffer zone was selected as possible suitable location for planning new biogas plant.

3. Results and discussions

All tomato processing industries were localised by their GPS coordinates in GIS map and combined with the already existing biogas plants localisation (Fig. 3).

As shown in Fig. 3 the territorial distribution of biogas plants is mainly located in the central area of Sicily, instead of the distribution of the tomato processing industries is highly concentrated in the South-East area and in the North-West area of the region, respectively. This distribution could generate increasing of GHG emissions due to the transportation during the logistic-supply phase, which could compromise the sustainability of the entire valorisation process.

All the tomato processing industries were face-to-face interviewed to acquire information related to the transformation process, to the amount of tomato processed and above all related to the amount of the tomato residues produced. Based on recorded data, as shown in Fig. 4, a heat map, by using tailored plugins available in QGIS software, was produced. Elaborated data were adopted for producing the Heatmap based on the amount of processed tomato residues.

The highest concentration of the processed tomato residues is mainly located within the Province of Ragusa and Enna which contribute with

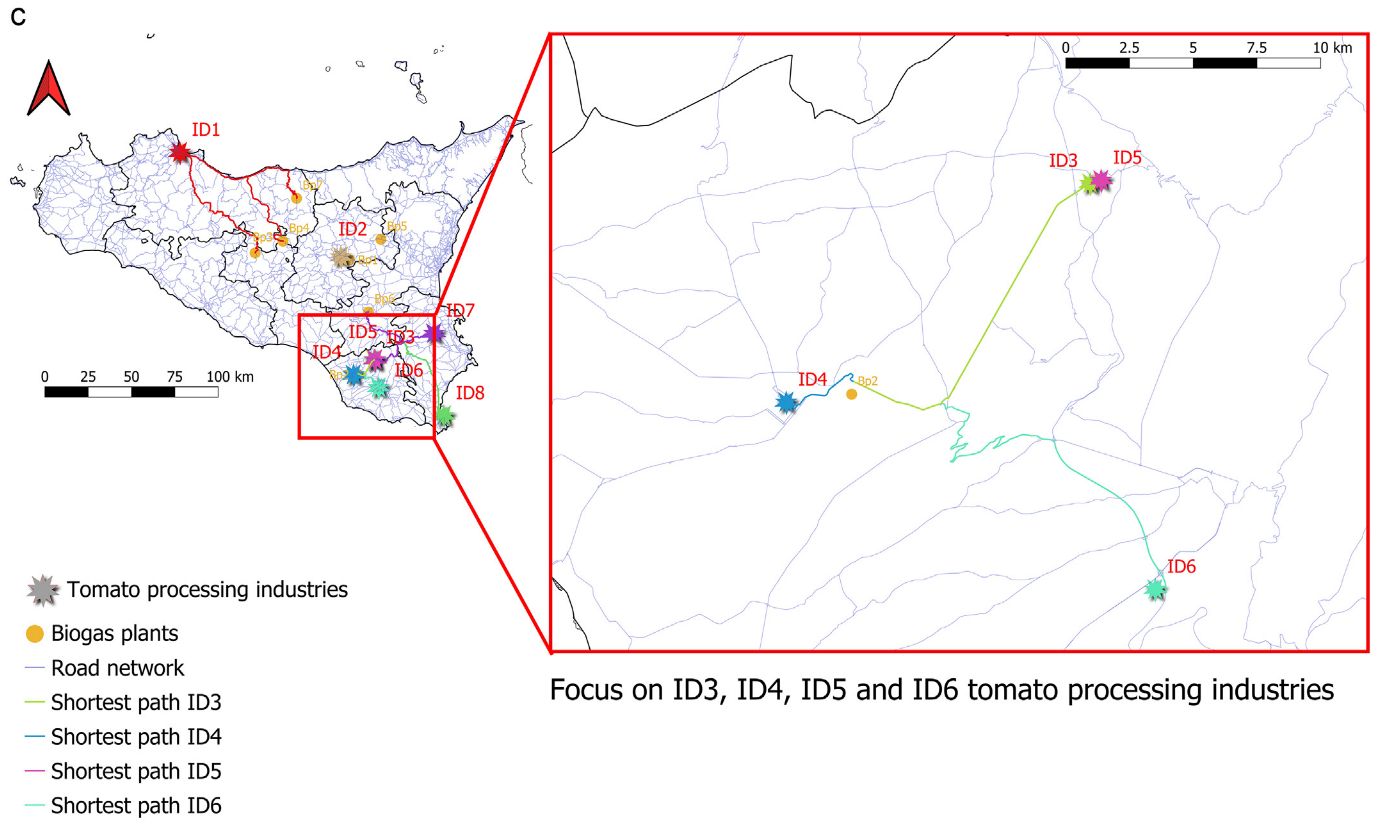

Fig. 7 (*continued*).

respectively one (ID2) and four (ID3, ID4, ID5, and ID6) processing industries. In detail, as shown in Fig. 4, the only one tomato processing industry (ID2) located in the province of Enna reached the highest concentration of production and therefore could mainly contribute to bioenergy production.

In order to deeply analyse the connection between tomato processing industries and existing biogas plants with the aim of identifying for each industry the suitable biogas plants for valorising their residues, a map with buffer zones was carried out (Fig. 5).

From each tomato processing industry (IDs), by setting 50-km distances, buffer analysis was carried out, aimed at defining the boundaries for choosing the suitable biogas plants for valorising tomato residues with the key criterion of minimising transportation impact. Areas around individual tomato processing industry with a central zone of 10 km radius and the areas with seven incremental 2.5 km radii from 2.5 to 50 km were set to establish the biomass collection boundaries for selecting the tailored biogas plant. For those processing industries in overlapping zones of neighbouring biogas plants, the transportation distances to different biogas plants were computed using the road graph plugin tool. The shortest transportation distance was the fundamental criterion that was adopted for determining which biogas plant should receive tomato residues from the industries in the intersection zones (Fig. 6).

As reported on Fig. 6, with the aim of defining the biogas plant for allocating of tomato residues, the road network was considered and the shortest paths from processing industries (IDs) to biogas plants (Bps) were carried out and reported on GIS map.

From Fig. 6 for each area a focus map was produced for detailing the shortest paths especially for those tomato processing industries located in the province of Palermo (ID1) and in the Province of Syracuse (ID7 and ID8) (Fig. 7).

Fig. 7a is focussed on the ID1 tomato processing industry with the aim of computing the distances from the nearest biogas plants Bp3, Bp4 and Bp7 (i.e., 102.22, 105.42, and 104.64 km, respectively). Among the biogas plants the closest with about 100 km-distance resulted Bp3, as reported on Table 1. Fig. 7b shows the shortest path computed for ID2 to reach the closest Bp (i.e., Bp1 with about 5 km-distance). Instead of the shortest path computed for supplying tomato residues of ID3 was about 14 km-distance to the closest Bp2 (Fig. 7c). In Fig. 7c also the shortest paths related to ID4, ID5, and ID6 were shown. Bp2 was selected as closest one for all the industries with a shortest distance of about 3.75, 14.78, and 22.06 km, respectively (Table 1).

Instead, as regard focus map related to ID7 and ID8, as reported on Fig. 7d, several paths were carried out before finding the shortest one, since no Biogas plants (Bps) were found close to both the considered industries. Therefore, Bp2 and Bp6, the closest biogas plants, were considered during the analysis. For ID7 processing industry the Bp6 was selected as closest one with an average distance of 67 km, since Bp2 was about 78 km distance. Results of ID8 shortest path analysis, demonstrated that Bp2 is the closest one with an average of 76 km-distance, instead of Bp6 that showed more than 100 km distance far. (Table 1).

On Table 1 all the determined biogas plants for supplying tomato residues from each tomato processing industry were reported and for each one the shortest distance for minimising transportation impacts was computed. Among the IDs, ID1 recorded the longest distance, about 100 km, instead the minimum distances were registered for ID4-Bp2, about 4 km, and for ID2-Bp1, about 5 km. ID1, ID7 and ID8 tomato processing industries resulted as the farthest ones from biogas plants, and therefore considerably influence the average distance, which was computed to be about more than 40 km.

Furthermore, data recorded from directly interviews of the tomato processing industries were elaborated and by valorising the tomato residues, which correspond at least 5 % (minimum rate) of the total amount of processed tomato, each industry could contribute to biogas production with at maximum about 12 thousand (e.g., ID2) Nm^3 per year to a minimum of more than 100 (e.g., ID4) Nm^3 per year.

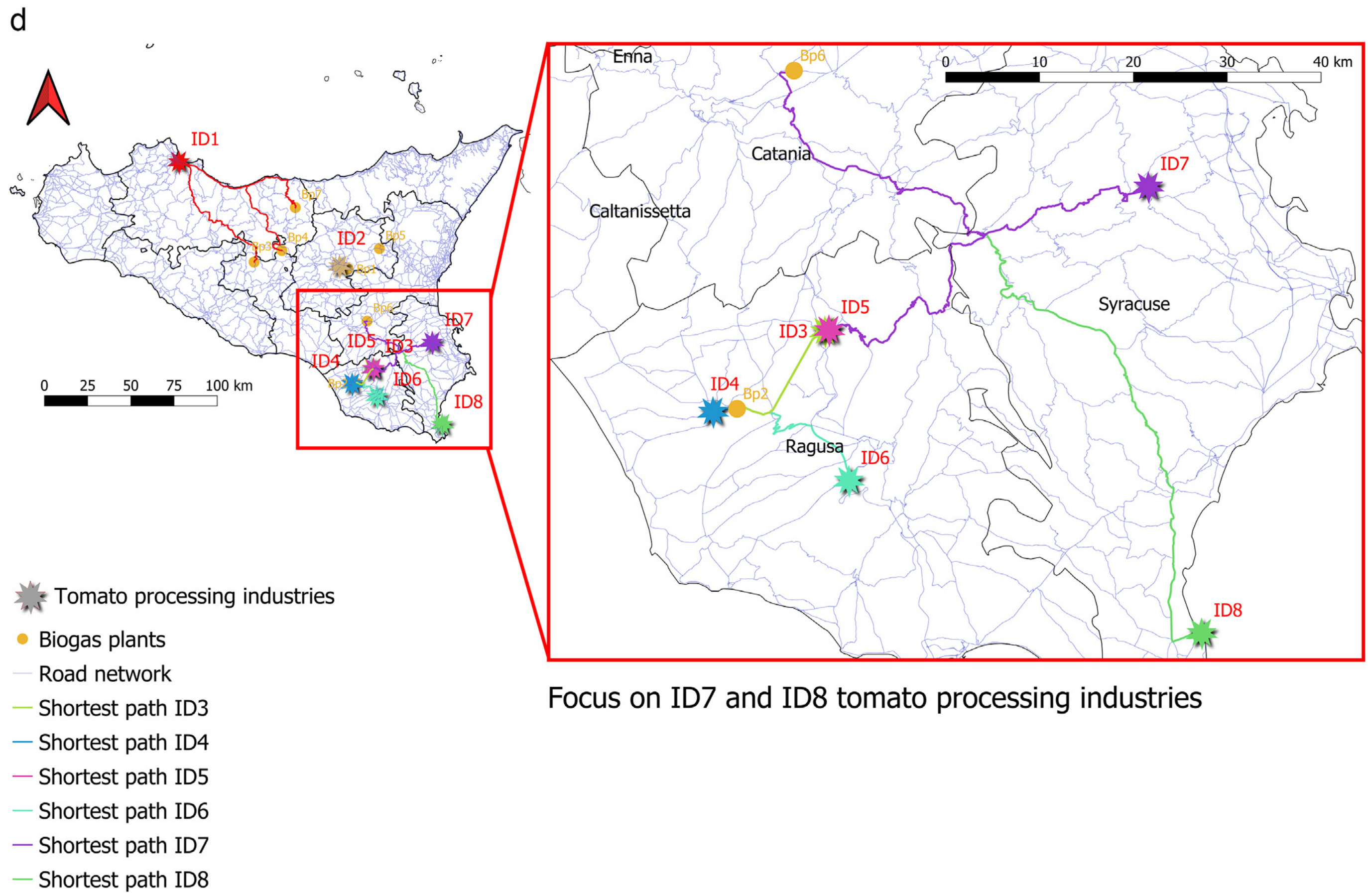

Fig. 7 (*continued*).

Therefore, with the aim of developing a sustainable valorisation of tomato residues, new suitable areas were investigated for reducing km-distances by minimising transportation impacts and overall, the related GHG emissions. In detail, sustainable planning of new biogas plant location close to both ID1, ID7 and ID8 were carried out in GIS software.

Firstly a 30-km radius buffer zone was set from the three selected IDs, and overlayed with the base map of Sicily. In Fig. 8 the overly analysis results were reported and the suitable areas at provincial level were highlighted.

Next step was focussed on establishing suitable locations within the selected areas. By focussing on ID1 area, firstly, the municipalities belonging to Palermo province were overlaid with the 30 km-distance buffer zone, then by adopting Polygons Centroid tool available in QGIS, the centre of the selected buffer zone was selected as suitable location for planning new biogas plant (Fig. 9). The centroid was localised within the area belonging to the municipalities of Altofonte and Santa Cristina Gela of Palermo province. The centroid position was not modified because of the coastline, but the developed model shows the possibility of adjusting if needed the centroid position by moving it exactly on ID1.

Then, the shortest path for supplying tomato residues from ID1 was computed and reported in Table 2.

It is possible to notice that, by adopting the new biogas plant location, only about 32 km-distance occurred for supplying tomato residues, which correspond about to 70 % less than the previously computed by selecting Bp3 as the closest one.

Same steps of the developed GIS-based methodology were followed for finding a suitable area for new biogas plant close to ID7 and ID8. As reported on Fig. 10, firstly the 30 km-distance buffer zones carried out respectively from ID7 and ID8 were joined and overlaid with the base map containing the municipalities belonging to the province of Syracuse. Next step regarded the localisation of the centre of the selected buffer zone as suitable location for planning new biogas plant (Fig. 10). As shown in Fig. 10 the centroid was localised between the municipalities of Noto and Avola of Syracuse province. From the centroid which was considered as the new suitable location for installing biogas plant, the shortest paths from ID7 and ID8 were computed about 47 km and 40 km-distances, respectively, as reported in Table 2. By comparing previously shortest distances computed for ID1, ID7 and ID8 respectively from Bp3, Bp6, and Bp2, and the new ones, obtained by planning sustainable locations, it is possible to notice from Table 2, that about 70 %, 30 % and 48 % less of km-distance can be reached.

This result could be important within the context of the sustainable valorisation of tomato residues, since if biogas plants were located too far from

Table 1
Results of the analysis of the shortest distance for minimising transportation impact.

Tomato processing industries	Biogas plants for tomato collecting[a]	Distances [km]	Processed tomato [t/y]	Biogas production[b] [Nm^3/y]
ID1	Bp3	102.22	1250.00	2071.63
ID2	Bp1	5.37	7263.00	12,031.16
ID3	Bp2	14.33	2000.00	3313.00
ID4	Bp2	3.75	100.00	165.65
ID5	Bp2	14.78	1200.00	1987.80
ID6	Bp2	22.06	3118.00	5164.97
ID7	Bp6	66.96	1000.00	1656.50
ID8	Bp2	75.73	200.00	331.30

[a] By minimising transportation distances.
[b] Considering 5 % (lowest) of tomato processed, and by applying the biomethane yield equal to 33.13 $Nm^3/t_{fresh\ matter}$ (Selvaggi et al., 2021b).

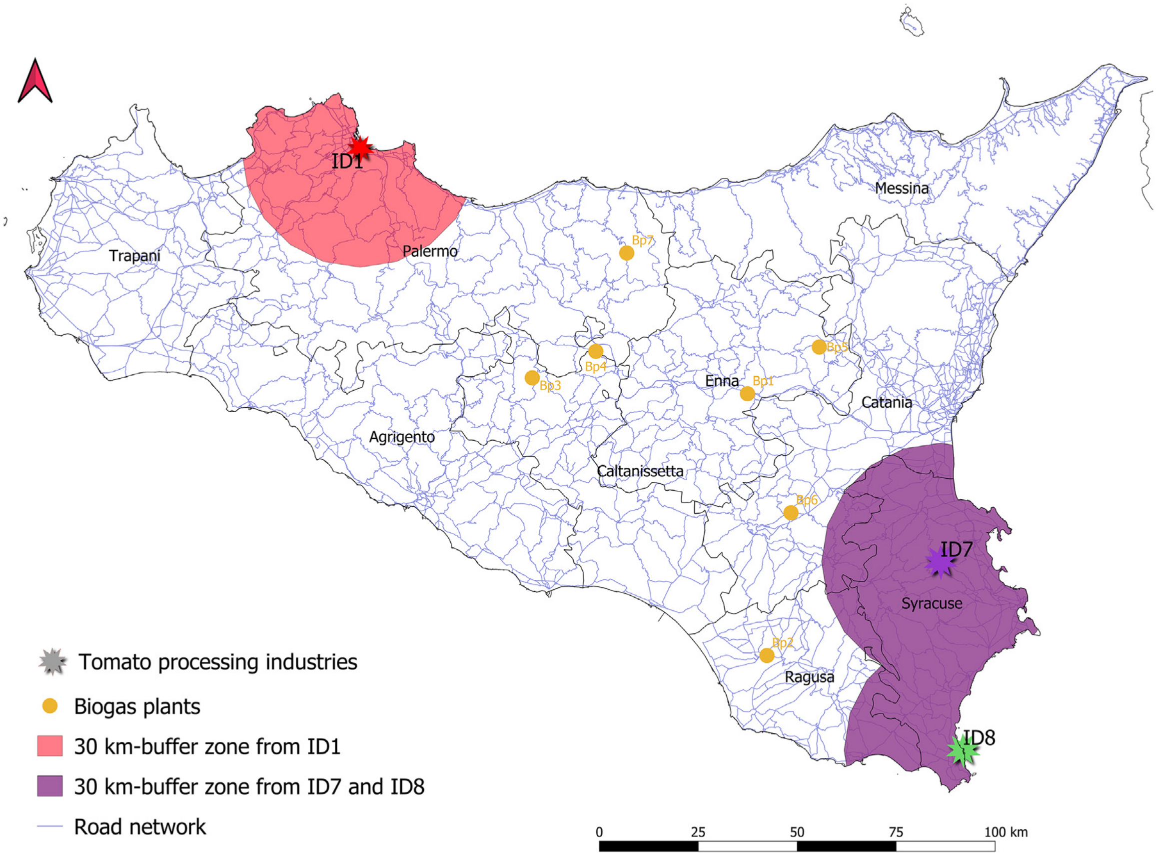

Fig. 8. Sustainable planning of new biogas plant's location close to ID1, ID7 and ID8 with the aim of minimising transportation impacts.

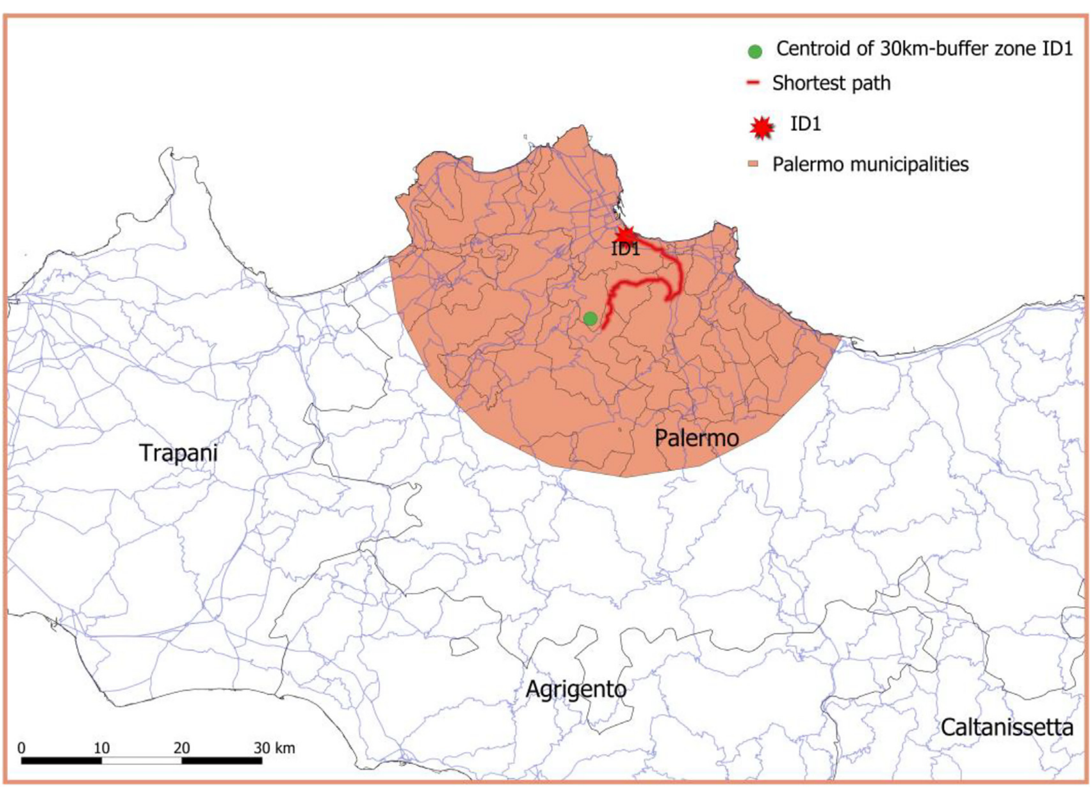

Fig. 9. 30 km-distance buffer zone by focussing on ID1 area obtained with polygons centroid tool available in QGIS.

Table 2
Results of the comparison between the distances from the tomato industries and the existent and new digesters achievable.

Tomato processing industries	Biogas plants	Distances [km]	New biogas plants location	Distances [km]
ID1	Bp3	102.22	Fig. 8	31.78
ID7	Bp6	66.96	Fig. 9	47.14
ID8	Bp2	75.73		39.94

the tomato processing industries, all the benefits, both economical and overall environmental, would be lost.

The new suggested suitable territorial areas for biogas plants location were reported on GIS map and overlaid with both the existing biogas plants and tomato processing industries-locations, as shown in Fig. 11. In green were reported the locations related to the new identified suitable areas for locating biogas plants, by minimising transportation impacts and reducing GHG emissions.

Based on their geographical distribution, the heat map, by taking into account all the biogas plants located within the study area (both existing and new ones), was produced and reported on Fig. 11.

The carried-out GIS map, shows finally, an equal distribution of biogas plants, that joins and groups the two East-West extremes of Sicily with a highest concentration within the central part of the island, by incorporating all the IDs (Fig. 11). This latter achieved result of biogas plants distribution within Sicily could help the development of biogas/biomethane sector in those areas in which it is still developing, by following the concept of circular economy, since several processing industries, not only tomato processing industries, could benefit from the new planned sustainable locations of biogas plants.

As shown in Fig. 11, the tailored new locations of biogas plants allow to achieve a more uniform distribution within the study area, by covering a wider territorial area. In detail, the North-West and South-East cost of the island could be involved by policy makers and practitioners within the biomethane chain. The two new locations were identified by considering the key criterion of minimising transportation impacts due to the logistic and supply phase with the aim of reducing environmental and economic impacts.

Although the achieved results were based only to a specific new feedstock, which could represent a limitation of the study, the developed methodology could be applied by considering any type of biomass, by providing strategic planning with the aim of sustainable developing biomethane sector. Furthermore, although, the new suitable locations are in small number, the developed methodology could be applied in any territorial area since it is not tailored just for the selected study area. The small number of locations is related to the selected study area, but the methodology could generally take into account more locations based on the study area in which it is applied.

In detail, the study demonstrated that the existing biogas plants do not cover the entire study area and the valorisation of tomato residues could be not sustainable from an environmental point of view due the distance between industries and biogas plants (in terms of kilometres). Therefore, the suggestion for suitable territorial areas were, in future, planning the development of biogas sector through new plants has been supplied. In detail two areas were considered suitable for enlarging biogas sector in a sustainable way, that added to the already existing ones allow to cover the whole study area. The achieved results, represent the first step of the utmost importance since they could be useful for policy makers for defining a strategic planning aimed at sustainable developing or enhancing the biogas/biomethane sector in Sicily.

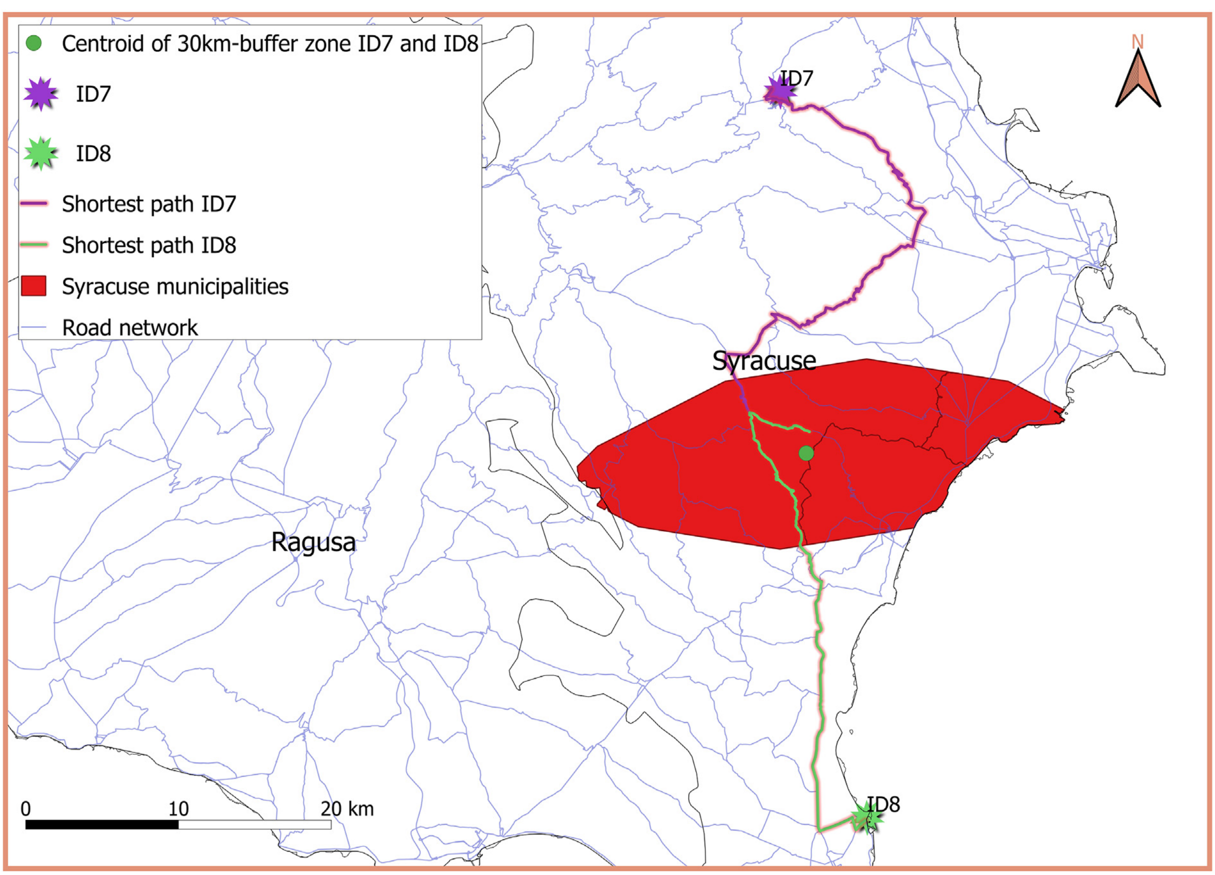

Fig. 10. 30 km-distance buffer zone by focussing on ID7 and ID8 areas obtained with polygons centroid tool available in QGIS.

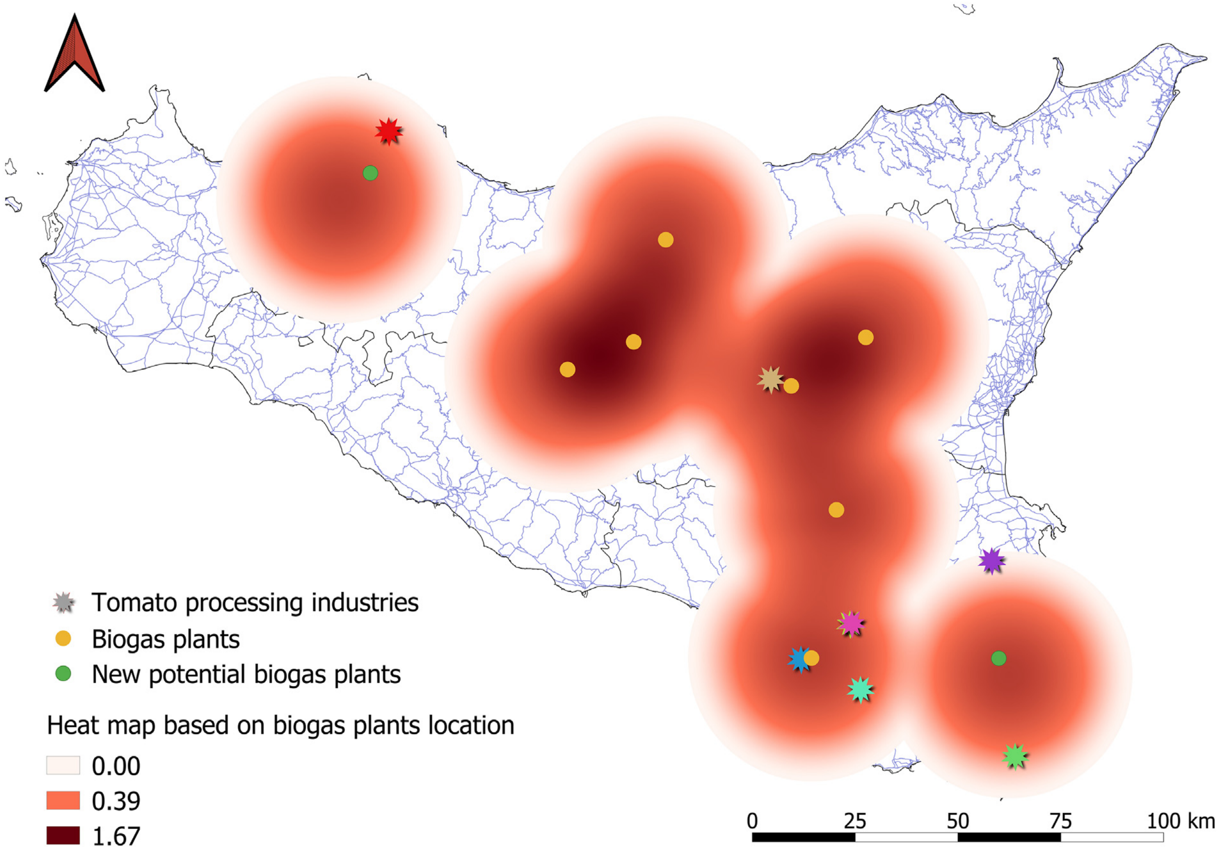

Fig. 11. Heat map based on the suitable strategical planning for biogas sector development by considering all the biogas plants located within the study area (both existing and new ones).

4. Conclusions

In this study, the developed methodology allowed to define new suitable locations of biogas plants by reaching a more uniform distribution within the whole study area. The achieved results could provide useful insights for both reducing environmental and economic impacts due to the logistics and supply phase and offering a scientific methodology to support policy makers and practitioners to strategic planning.

It is worldwide recognized that, with the aim of drastically reducing the logistic impact on the environmental and economic aspects of the biomass resource, biomass transport chains must be considered. The impact of transporting low-density, high-moisture agricultural residues is the main barrier that avoid their use as an energy source. Transporting feedstocks to a centralized biomass plant location (i.e., anaerobic digestion plant) is a key aspect of any bio-energy project.

In this regard, the achieved results could be crucial to support the strategic planning development of a future sustainable biogas chain in line to circular economy. In detail, the switch from a linear to a circular economy will reduce pressure on natural resources and will generate sustainable growth and, above all, jobs.

By adopting sustainable planning policies, it is possible to achieve new wages employment for farmers and allows to diversify their sources of income. With complementary policies, adopting strategic planning could help support a developing country structural renovation. Additionally, the adoption of embracing a circular economy that aimed at emphasizing the reuse, the recycling, the remanufacture and repair of goods, will produce a lot of new opportunities of employment opportunities across the world because of these actions will replace the traditional model of "extract, make, use and dispose".

Furthermore, the achieved results can provide a start point for wider and deeper investigation of bioenergy logistic chains, by adopting the Life Cycle Assessment (LCA) or Life Cycle Costs (LCC) approaches. In this regard, future research could apply the methodology developed in this study by considering different territorial areas and/or different biomass source in order to contribute in a sustainable way at developing tailored strategic planning.

CRediT authorship contribution statement

Francesca Valenti: Conceptualization, Data curation, Formal analysis, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing. **Monica C.M. Parlato:** Writing – review & editing, Visualization. **Biagio Pecorino:** Visualization. **Roberta Selvaggi:** Conceptualization, Data curation, Formal analysis, Investigation, Writing – review & editing, Supervision.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

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

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