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Biofuels

Environmental productivity index GIS-based model to estimate prickly pear biomass potential availability for biogas production

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Abstract

Nowadays, climate change is the environmental issue facing the world. To reach the 2030 European Union goals, recently, biogas production through anaerobic digestion has developed significantly, by using alternative biomass sources due to the competition between food and no-food products. In this regard, *Opuntia ficus-indica* (*OFI*) has been suggested as a suitable new biomass for producing biomethane within the context of circular economy. In this study, a predictive methodology was applied by combining the Nobel model of environmental productivity index (EPI) and geographic information system (GIS), with the aim of estimating *OFI* biomass amount, as well as biogas and electricity potential production. The GIS analyses allowed the identification of the most suitable territorial areas for producing biogas from *OFI*, and an estimation of electricity production. The achieved results are highly valuable information for strategic planning of biogas sector development and could be relevant to the intervention priorities established by the EU.

1 | INTRODUCTION

Demand for renewable biomass-based carbon resources to use for lignocellulosic biofuels is expected to increase in the future due to the reduction of greenhouse gas (GHG) released into the atmosphere (Aosaar et al., 2012; Yang et al., 2015). Nowadays, the production of biogas by anaerobic digestion has developed significantly, by using alternative biomass sources due to the competition between food and no-food products (Dale et al., 2016). Furthermore, water availability is the crucial factor that limit the cultivation of bioenergy crops; therefore, on those water-limited areas the crassulacean acid metabolism (CAM) species such as *Agave* (Agavaceae) and *Opuntia* (prickly pear) could be suitable biomasses due to their growth characteristics that allow to thrive in semi-arid regions (Yang et al., 2015).

Prickly pear is widely used within the food, pharmaceutical and cosmetic, and textile industries (Ortiz-Laurel et al., 2014) but is also recognized as a bioenergetic crop, for production of lignocellulosic biofuels, biogas, and biofertilizers. Crops characterized by a CAM, such as *Opuntia ficus-indica* (*OFI*), are a recommended resource for alternative energy production as they have a high potential for biomass production (Nobel & de Cortázar, 1991; de Cortázar & Nobel, 1992; de Cortázar & Varnero, 1999; Mason et al., 2015). In this regard, it is well known that the chemical composition of the biomass, the degree of solubilization, and hydrolysis of the organic matter within the digester are crucial factors for the anaerobic digestion process in order to obtain a high anaerobic biodegradability and a high biogas yield (Santos et al., 2016; Valenti, Porto, Selvaggi, et al., 2018). Because it is

Abbreviations: BMP, Biochemical Methane Potential; CAM, crassulacean acid metabolism; DM, dry matter; EPI, environmental productivity index; GIS, geographic information system; HWSD, Harmonized World Soil Database; *OFI*, *Opuntia ficus-indica*; PAR, photosynthetically active radiation.

demonstrated that a large fraction of the stems, also known as cladodes, is biodegradable, this implies that they could constitute an important source of feedstock for biogas production (Jigar et al., 2011). On the other hand, the biomass from cladodes contains high organic matter but low nitrogen (Jigar et al., 2011); therefore, it needs to be mixed with other feedstocks richer in nitrogen content, such as manure (Valenti et al., 2020), in order to maximize the biogas production in terms of methane content (Valenti, Porto, Dale, et al., 2018; Varnero & de Cortázar, 2013). Furthermore, waste material from *OFI* crop pruning can also be used as a feedstock to produce biogas and biofertilizers through the anaerobic digestion process, within the concept of Biogasdoneright (Dale et al., 2016). With regard to this concept, the by-products (i.e., waste material from *OFI* crop) can be used for producing biogas in a more sustainable way (Selvaggi & Valenti, 2021; Valenti et al., 2017).

As worldwide recognized, prickly pear has an excellent biomass production capacity still under unsuitable soil and climate conditions, thanks to its high efficiency in the use of water (Ramos-Suàrez & Martinez et al., 2014; Santos et al., 2016). However, the productivity of *Opuntia* is influenced by the average temperature, and by solar radiation within the wavelength range between 400 and 700 nm. The *Opuntia* plant dies at temperatures below −5 ˚C and could survive at soil temperatures around 70 ˚C, yet with permanent damage. The maximum production of *Opuntia* is reached within the 5–20 ˚C range (Nobel, 1989). Furthermore, the biomass production from *Opuntia* is considered stable over time because it is not affected by rainfall events that are irregularly distributed during very dry periods (Santos et al., 2016).

Based on the main research studies found in the literature, Table 1 shows a comparison between the main parameters due to the biogas production in different contexts.

Santos et al. (2016) compared different *OFI* varieties in Brazil and found that the average productivity of fresh biomass (raw matter) of prickly pear reached almost 90 t ha^{-1} yr^{-1} and the productivity of DM was equal to 8 t ha^{-1} yr^{-1}. Furthermore, they highlighted that, under favorable and suitable water irrigation conditions, prickly pear can reach up to 45–50 t ha^{-1} yr^{-1} of DM production, which could be considered a very high yield if compared to those of the most commonly used crops for biomass production (Ramos-Suàrez & Martinez, 2014; Santos et al., 2016). In cultivations of *OFI* located in Argentina it has been found that, in sandy soils and in those territorial areas characterized by 300 mm of rainfall, the productivity of DM ranged between 2.1 and 2.4 t ha^{-1} yr^{-1}, which corresponds to a mean rainfall-use efficiency factor (RUE) of 7.4 kg ha^{-1} yr^{-1} mm^{-1} of DM. These yield values are lower than those found for arid and sandy soils, which are characterized by an average annual rainfall ranging between 200 and 400 mm, and by a yield of about 15–22.5 kg ha^{-1} yr^{-1} mm^{-1}. On the contrary, on silty sand soils, with rainfall slightly above 200 mm, the productivity of DM reached values of about 0.75 t ha^{-1} yr^{-1} and a mean RUE of only 3.5 kg ha^{-1} yr^{-1} mm^{-1} (Guevara & Estevez, 2001).

Core Ideas

- The use of *Opuntia ficus indica* biomass for anaerobic digestion was assessed.
- The methodology was applied by combining models and spatial analysis tools.
- The study was carried out from territorial data acquired at local scale.
- Based on bioclimatic data, the environmental productivity index was estimated.
- The most suitable areas for producing biogas and electricity per year and per hectare were computed.

The estimation of the theoretical potential of biogas production from the biomass of prickly pear was carried out by Santos et al. (2016) by considering the average productivity value of the dry biomass of three selected species, giant palm (*Opuntia ficus-indica*), palma redonda (*O. ficus-indica*), and palma miúda [*Nopalea cochenillifera* (L.) Mill.], which was equal to 7.9 t ha^{-1} yr^{-1}, with an average value of volatile solids (VS) equal to 91%. Therefore, by taking into account all the above-mentioned parameters, the potential biogas production was estimated to be 3,717 m^3 ha^{-1} yr^{-1}. Similar results of potential biogas production were found in the literature for other traditional energy crops such as maize (*Zea mays* L.) (5,780 m^3 CH_4 ha^{-1}), alfalfa (*Medicago sativa* L.) (3,995 m^3 CH_4 ha^{-1}), and forage beet (*Beta vulgaris* L.) (5,800 m^3 CH_4 ha^{-1}) (Santos et al., 2016).

Mason et al. (2015) compared different datasets for *OFI*, unfertilized rain-fed crops and a manual harvest, with limited availability of water. It was found that increased yields per hectare because greater planting densities could be achieved through mechanized harvesting. Furthermore, the resilience of these plants to drought leads to a decrease in production rather than crop failure. Through the application of the methodology reported by Mason et al. (2015), the gas yield production was estimated to be 325 CH_4 L kg^{-1} and electricity from biomass of DM was equal to 1.33 $MWht^{-1}$.

De Cortázar and Nobel (1990) predicted EPI for 253 regions worldwide by using data from 1,464 weather stations within 60° of the equator. First, the climatic data were used to calculate daily values of a PAR index, a temperature index, and a water index. In this research study, *OFI* productivity of 32 t ha^{-1} $year^{-1}$ was predicted for western South America with rainfall above 331 mm.

Comparetti et al. (2017) carried out a research work aimed at estimating the potential production of biogas and,

TABLE 1 Main data and parameters from experimental analyses carried out on *Opuntia ficus-indica* (*OFI*)

Reference	Soil texture	Site	Main annual rainfall	Raw matter	Dry matter	Mean rainfall-use efficiency factor	BMP	Biogas production	CH_4 per cubic meter of biogas	Electricity	Electrical energy production
			mm yr^{-1}	——t ha^{-1} yr^{-1}——		kg ha^{-1} yr^{-1} mm^{-1}	m^3 t^{-1} DM^{-1}	m^3 ha^{-1} yr^{-1}	%	kWh m^{-3}	kWh ha^{-1} yr^{-1}
Santos et al. (2016)	Semi-arid	Alagoas, Pernambuco and Paraíba, Brazil	450[a]	89.7	7.9	18[b]	517	3,717	60	1.25	4,646
Guevara and Estevez (2001)	Sandy	Argentina	300	na	2.1–2.4	7.4	na	na	na	na	na
	Arid and sandy	Argentina	200– 400	na	3–9	15–22.5	na	na	na	na	na
	Silty sand	Argentina	200	na	0.75	3.5	na	na	na	na	na
Obach and Lemus (2006)cited by Santos et al. (2016)	na	na	na	na	300	na	58[d]	na	52	1.5	23,400
Mason et al. (2015)	Sandy	Mutumayu, Kenya	500–600	120[c]	40	80—67[b]	325	na	na	na	53,200
De Cortázar &Nobel (1990)	Arid and semi-arid	western South America	331	na	32	97[b]	na	na	na	na	na
Comparetti et al. (2017)	Semi-arid	Sicily	300	na	29[b]	97[b]	300	770[b]	56[b]	0.109[b]	112[b]
Rosato (2014)	Semi-arid	Sicily	300	150[b]	12	40[b]	350	3,600[b]	60	na	na

Note. BMP, biochemical methane potential; DM, dry matter; na, not applicable.

[a]Data acquired from https://it.climate-data.org/.

[b]Computed values from data.

[c]Computed average values for different planting densities.

[d]Unit of measure: m^3 t^{-1} SV^{-1}.

indirectly, biomethane or electrical and thermal energy in Sicily. As a result, they found a biomass production from prickly pear equal to 8.5 t ha^{-1} yr^{-1} of DM with an average annual rainfall of 300 mm, a value similar to Spain (Rosato, 2014), and by applying a BMP value of about 300 Nm^3 t^{-1}, the potential production of biogas was estimated.

Furthermore, a conversion factor suitable for estimating the amount of produced electricity was proposed by several authors (Ortiz-Laurel et al., 2014; Pompermayer & Paula, 2000). In detail, it was found that 1 m^3 of biogas containing about 60% methane allows the production of 1.25 kWh; therefore, it was estimated that biomass from prickly pear allows an electrical energy production equal to 4,646 kWh ha^{-1} yr^{-1} and from the analysis of the produced biogas it has a calorific value equal to 5,500 kcal m^{-3}, according to Pompermayer and Paula (2000).

Obach and Lemus (2006) estimated a production of 23,400 kWh ha^{-1} yr^{-1} based on an average production of 300 t ha^{-1} yr^{-1} of raw matter, with a biogas potential production of 58 m^3 per t SV^{-1}(with the 52% of methane content) and 1.5 kWh m^{-3} of electrical energy. Furthermore, by considering that the average electricity consumption of a Brazilian household is equal to 200 kWh $month^{-1}$, biomass from prickly pear would allow the sufficient production of electricity to meet the annual consumption of about two houses (Santos et al., 2016).

Table 1 highlights that many studies in the field did not evaluate the potential biogas production as well as the electricity from biomass. Therefore, in the research outlined in this paper, the computation of biomass, biogas, and bioenergy production from *OFI* aims at contributing to the needed increase of knowledge in the field, as highlighted in this state of the art from the literature studies.

Based on the various possibilities offered by the valorization of this crop (Feyisa et al., 2022), it is therefore necessary to acquire information on productive capacity of *OFI* and its localization at the territorial level in order to evaluate its possible use for energy production.

In this context, several studies have been carried out on biomass-bioenergy systems in recent years by using the geographic information system (GIS) tool, which makes it possible to both manage and analyze different types of georeferenced information by adopting the concept of map layers (Bambara et al., 2019; Valenti, Zhong, et al., 2018). Some research studies have covered subjects including biomass to biofuel feedstock and conversion technologies, biomass supply chain design and management including modelling and optimization approaches (Ba et al., 2016; Barbosa-Póvoa et al., 2017; Ghaderi et al., 2016). Erre et al. (2009) proposed a GIS-based methodology to analyze the capacity of adaptation of two local biotypes of *OFI* [i.e., *Opuntia ficus-indica* (L.) Mill. and *O. amyclaea* Ten] to different types of land and environmental conditions. Land-use planning and strategic management in agriculture, through the use of GIS tools, are effective tools to achieve sustainable development (Ghosh & Kumpatla, 2022). Determination of the suitability of land-use types for a certain area, that is, setting the priority of agricultural land-use types, is an important part of land-use planning (Akpinar et al., 2004).

The application of GIS tools has been widely proposed in several research studies aimed at defining indices and indicators suitable for describing the potential production of biomass in Mediterranean areas and for estimating the potential production of biogas (Selvaggi et al., 2021; Valenti et al., 2016; Valenti & Porto, 2019). In these studies, the definition of the indicators was carried out on the basis of crop coverage derived from digital cartography and orthophotos.

In other studies, the main objective concerned the analysis of the productivity of the plant species in the examined area. Owen and Griffiths (2014) applied the environmental productivity index (EPI), computed by following the methodology proposed by Nobel and Meyer (1985), for the development of a geospatial model aimed at estimating the bioethanol yield potential of four CAM crops (i.e., *Agave fourcroydes* Lem., *A. salmiana* Otto ex Salm-Dyck, *A. tequilana* F.A.C.Weber, and *OFI*) in Australia. In this research, GIS software was used to combine climatic data with titratable acidity responses as a function of photosynthetically active radiation (PAR), temperature, and precipitation in order to evaluate the influence of environmental conditions on the species distribution. However, in the study *OFI* bioethanol yield potential was not computed, because it did not match the environmental responsibility (ER) criteria, defined by the authors, as a "best" option to identify potential trial sites outside areas that support high-yield agriculture (Owen et al., 2016).

Therefore, by defining tailored indices, this study aims at evaluating the feasibility of using *OFI* biomass for anaerobic digestion and its territorial distribution, as well as estimating the biogas and electricity potential production in a territorial area of Sicily. By following the methodology proposed by Owen and Griffiths (2014), this study was carried out through the application of GIS software and EPI model. Specifically, the aim was to express the prickly pear productivity based on the soil and climatic variables of the considered territorial area. To this end, the province of Catania was selected as the study area for the computation of the EPI for *OFI*, by taking into account the necessary environmental parameters acquired by local weather stations during a 10-yr time interval. Furthermore, on the basis of the evaluated amount of potential biomass, the biogas per unit of surface area and the electricity potentially obtainable per unit of surface area were computed by taking into account the estimated EPI, the production of dry matter (DM), and the results of the Biochemical Methane Potential (BMP) test.

2 | MATERIALS AND METHODS

The methodology applied in this study was carried out through the following steps, according to Owen and Griffiths (2014):

1. Analyses and elaborations of data related to precipitation, PAR, and average values of the minimum and maximum temperatures acquired by the weather stations located in the area, in order to define eco-physiological indices useful for the EPI computation.
2. Analyses of the soil characteristics nearby the weather station, by evaluating the clay, silt, and sand values of the soils in order to define the soil water retention, in order to define an eco-physiological index useful for the EPI computation.
3. Computation of the eco-physiological indices, through the use of the ArcGIS software (Esri), in order to estimate EPI by taking into account variations of solar radiation, water content, and temperatures.
4. Application of *kriging* interpolation tool of GIS software, to produce tailored maps with the aim of showing the EPI distribution at the territorial level.
5. Estimation of the potential production of biogas, by using the ArcGIS software, based on literature data related to both the biomass production and its yield.
6. Estimation of the electricity production based on both the estimated potential production of biogas and literature data (e.g., biogas-electricity conversion factors).

2.1 | Definition of eco-physiological indices and computation of the EPI

Based on the methodology proposed in many research studies (Nobel, 1988; Nobel & Meyer, 1985; Nobel & Quero, 1986), the first step of the study provides forecast information on the biomass productivity and makes it possible to determine these values in different areas, different climatic conditions, and different soils.

The EPI depends on the minimum and maximum temperature (through the temperature index, I_t), rainfall (through the rainfall index, I_w) and PAR, as a fraction of solar radiation, (through the ecophysiological response to PAR index, I_p), and it was calculated by applying the following equation (de Cortázar & Nobel, 1986; Nobel, 1988; Nobel, 1989; Nobel & Valenzuela, 1987) (Equation 1):

$$\text{EPI} = I_w \times I_t \times I_p \tag{1}$$

In detail, the EPI was computed as an annual average value by using monthly data. The EPI equation was the following (Equation 2):

$$\text{EPI}_{\text{annual}} = \sum_{m=1}^{12} \frac{(I_w \times I_t \times I_p)_m}{12} = \frac{I_w^{\text{JAN}} \times I_t^{\text{JAN}} \times I_p^{\text{JAN}} + \cdots + I_w^{\text{DEC}} \times I_t^{\text{DEC}} \times I_p^{\text{DEC}}}{12} \tag{2}$$

where m is related to the month of the year.

In the following section the contribution provided by the individual parameters adopted for the EPI calculation is detailed.

2.2 | Rainfall and soil texture parameters

In order to compute the EPI it was necessary to evaluate the relationship between rainfall and the current water availability in terms of soil water potential.

The soil water potential (Ψs) has mainly negative values; therefore, a high potential requires a low water retention capacity, and a low energy is required to the plants for the absorption. On the contrary, if the soil water potential is low, the soil strongly holds water, and a considerable effort to absorb water is required to plants.

Furthermore, the soil water potential depends on rainfall and soil texture; therefore, the necessary analyses for EPI estimation, required data on soil texture, that is, the calculation of the clay, sand, and silt fraction, neglecting the value of the soil organic fraction.

According to Nobel (1988), CAM plants are very sensitive to the lack of water in the soil and their soil water absorption commonly takes place between −0.2 and −0.4 MPa for Ψ_s and, under stress conditions, this value is around −0.5 MPa. Therefore, water absorption takes place when Ψs > −0.5 MPa.

The soil water potential is computed as a function of the water content (ϑ) and texture classes (C = clay; S = sand), by using the following equation (Acevedo et al., 1983) (Equation 3):

$$\Psi_s = A \times \vartheta^B \tag{3}$$

in which A and B depend on soil textures through the following relations (Equations 4 and 5):

$$A = 100 \exp\left[a + b(\%C) + c(\%S)^2 + d(\%S)^2 (\%C)\right] \tag{4}$$

$$B = e + f(\%C)^2 + g(\%S)^2 + g(\%S)^2 (\%C) \tag{5}$$

where the parameters a, b, c, d, e, f, and g were obtained from Saxton et al. (1986).

The computation of the gradient function ($g_{i,\,\text{soil}}$) for each single type of soil was carried out by means of a linear proportion between the $\theta_{sandy\ soil}$ and $g_{i,\ sandy\ soil}$ while the following equation (Equation 6) is considered valid for a wide range of textures and for h values within unsaturated soil conditions (Saxton et al., 1986). Consequently, the day-duration (U_{days}) was estimated as a function of precipitation R, when the condition $\Psi_s > -0.5$ MPa occurs by the following equation:

$$U_{days} = g_i \times R \tag{6}$$

The effective number of days per month (U_e) when plant carbon uptake is not rate-limited by water availability was determined by the following equation (Equation 7):

$$U_e = g_i \times R \times f_d \tag{7}$$

where $f_d = 1.92$ for *OFI* and identifies the value of the titratable plant acidity (TA) within a phase of water deficit through the calculation of the ratio between titratable plant acidity under drought conditions (TA_d) and TA under optimal conditions, by considering a 28-d interval (Acevedo et al., 1983; Nobel, 1989; Nobel & Valenzuela, 1987; Saxton et al., 1986).

Finally, the rainfall index I_w was computed by the following equation (Equation 8):

$$I_w = U_e / D_m \tag{8}$$

where D_m is the number of days in a month. Therefore, it was established that $I_w = 1$ when $U_e/D_m \geq 1$ (Nobel, 1988).

2.3 | Temperature parameters

The carbon absorption capacity of *OFI* demonstrates that this plant is strongly affected by temperatures. Therefore, the definition of the temperature index I_t aims at representing this absorption capacity based on temperatures during both day and night.

Consequently, the analysis of both the monthly minimum night-time temperatures I_t min and the monthly maximum day-time temperatures I_t max was necessary to determine the temperature index I_t, by applying the following equations (Nobel, 1988; 1989; Nobel & de Cortázar, 1991; Nobel & Israel, 1994) (Equations 9, 10, and 11):

$$I_{t\ min} = -0.0041t_{min}^2 + 0.117t_{min} + 0.186 \tag{9}$$

$$I_{t\ max} = -0.0002t_{max}^2 + 0.0104t_{max} + 0.875 \tag{10}$$

$$I_t = I_{t\ min} / I_{t\ max} \tag{11}$$

2.4 | Photosynthetically active radiation parameter

In previous research studies carried out on *OFI* it was found that the CO_2 absorption during night-time, as well as the increase of acid concentration, and their ratio are influenced by the amount of PAR that the plant is able to absorb during the day (Nobel & Hartsock, 1983; de Cortázar & Nobel, 1986).

Therefore, the ecophysiological response to photosynthetically active radiation index, I_p, depends on PAR and it was computed according to the following equation (Nobel, 1988; Nobel & de Cortázar, 1991; Nobel & Israel, 1994; Nobel et al., 1987; Nobel & Valenzuela, 1987):

$$I_p = -0.0007p^2 + 0.057p - 0.1856 \tag{12}$$

in which p stands for the PAR value. When $p \geq 35$ mol m^{-2} d^{-1}, the index I_p was set equal to 1.

2.5 | Evaluation of potential production of biomass, biogas, and electricity from *OFI*

In order to estimate the amount of potential biogas per unit of surface area, after the computation of the EPI, it is necessary to take into account the data related to the DM content as well as the BMP tests of the species.

The biomass yield or potential biomass production (PBp) of *OFI*, expressed in [t yr^{-1} ha^{-1}], was estimated by the following equation, as the product of the EPI and the maximum DM productivity (PBp_{max}) expressed in tonne per hectare and per year, by considering optimal irrigation conditions and a value of 8 t ha^{-1} yr^{-1} for irrigation plant density (Equation 13):

$$PBp = PBp_{max} \times EPI \tag{13}$$

In this equation, the value of PBp_{max} was considered equal to 8.5 t ha^{-1} yr^{-1}, in accordance with other research studies carried out on the same territorial area (Comparetti et al., 2017). Furthermore, by considering the pessimistic value of BMP, that is, equal to 300 Nm^3 t^{-1} of DM per year, the total potential production of biogas (Bp) expressed in Nm^3 per hectare and per year can be obtained by the following relation (Equation 14):

$$Bp = PBp \times BMP \tag{14}$$

Additionally, the potential production of electricity obtainable from biogas-conversion was computed by using the conversion factor proposed by Pompermayer and Paula (2000) for the estimation of electricity. In detail, because a cubic meter of biogas containing about 60% of methane allows the production of 1.25 kWh, the electric energy production Pr_{eep} for 1 yr expressed in kWh yr^{-1} ha^{-1} was estimated by the following relation (Equation 15):

$$Pr_{eep} = 1,25 \times Bp \quad (15)$$

Next, the computation of the surface area *S* in terms of hectares of each considered municipality, allows achieving the potential total production of biogas and electricity per municipality by using the following relations, respectively (Equations 16 and 17):

$$Bp_{tot} = PBp \times BMP \times A \quad (16)$$

$$Pr_{eep\ tot} = 1,25 \times Bp_{tot} \quad (17)$$

3 | CASE STUDY

3.1 | The study area

The study was carried out in the Province of Catania. Catania province covers an area of 3,552 km^2, includes 58 municipalities, and is located on the East coast of the island. It is characterized by the presence of Etna, one of the largest active volcanoes in the Mediterranean area, which reaches 3,350 m asl (Carbone et al., 2009).

The average temperature within the Sicilian region is quite high everywhere, ranging from 19 ˚C of the coastal areas to 13 ˚C of the higher inland areas. January is the coldest month and has a temperature value close to the coastal areas of about 10 ˚C, as it is influenced by the sea. The month of July is the hottest one with an average value of temperature that ranges from 25 to 26 ˚C, close to the coastal areas, to 18 ˚C in the mountainous ones (Venturella, 2004).

The province of Catania offers a great climatic variety, which is influenced by the altitude and the proximity to the sea (Carbone et al., 2009). The area of the Catania Plain has a semi-dry climate with low precipitations, mostly concentrated during the autumn season. Moreover, this area is characterized in all seasons by a strong temperature range from day to night. The coastal area is characterized by a very hot summer season and mild winter, with rainfall mainly concentrated in the autumn–winter period. Conversely, in the internal areas the winter temperatures are lower than those recorded in the coastal zone, while summer ones are quite similar (Carbone et al., 2009; Leanza et al., 2022).

Furthermore, based on a study carried out by the Agriculture and Forestry Department of the Sicilian region on the analysis of data from 1965 to 1994, in the province of Catania three main areas can be distinguished based on the average yearly temperatures: the coastal and plain areas, belonging to the municipalities of Acireale, Catania, Piedimonte Etneo, and Ramacca, with values of about 18 ˚C; the internal hilly area belonging to the municipalities of Mineo and Caltagirone, which reported yearly temperatures of 16–17 ˚C; and the volcanic area, where the temperature values decrease with altitude (Cartabellotta et al., 1998).

With regard to rainfalls, the highest annual values (about 960 mm) in the whole Sicily are recorded on the eastern and northeastern territorial areas of Etna, with a value that proportionally increases with altitude, reaching about 1,200 mm at the top of Etna. On the contrary, very low annual rainfall values (about 500 mm) are found on the western and southwestern territorial areas of Etna, particularly in the municipalities of Paternò, Motta Sant'Anastasia, Maniace, and Ragalna. Low annual rainfall values (about 500 mm) are recorded in the South of the province ranging from 402 mm in Ramacca municipality to 579 mm in Mirabella Imbaccari municipality. The other values acquired from the weather stations located in Caltagirone, Mineo, and Vizzini municipalities ranged between the above-reported values (i.e., 402 and 579 mm) (Cartabellotta et al., 1998).

Moreover, based on the surveys carried out in Sicily by the Ministry of Economic Development, 1 million m^3, 2.5 million m^3, and 7.2 million m^3 of natural gas are used by industries, to produce thermal and electrical energy, and for domestic heating, respectively (Comparetti et al., 2017). In this regard, the potential biogas production from biomass of *OFI* could contribute to meet the demand for natural gas.

3.2 | EPI within the study area

Twenty-three regional weather stations (Table 2; Figure 1), managed by the Sicilian Agro-meteorological Information Service (SIAS), were taken into account in this study. The weather stations acquire climatic data, such as air temperature and PAR, at different locations and the Service provides them to the users at various granularities.

Among these weather stations, 14 are located in the Province of Catania and 9 are located in the other neighboring provinces (i.e., Messina, Enna, Syracuse, Ragusa, and Caltanissetta). The considered number of weather stations has proven to be adequate in order to obtain a uniform distribution of data throughout the territory with a good coverage in coastal and mountainous areas.

Furthermore, the decision to include in this study weather stations located outside the Province of Catania was due to the need to determine a good data spatial coverage also in those areas located close to the administrative boundaries.

In detail, the daily average data of maximum and minimum temperatures, rainfalls, and PAR, recorded from 1 Jan. 2006 to 1 Jan. 2016 were elaborated.

The PAR index was computed from the solar radiation data, acquired from SIAS database, and expressed in MJ m^{-2},

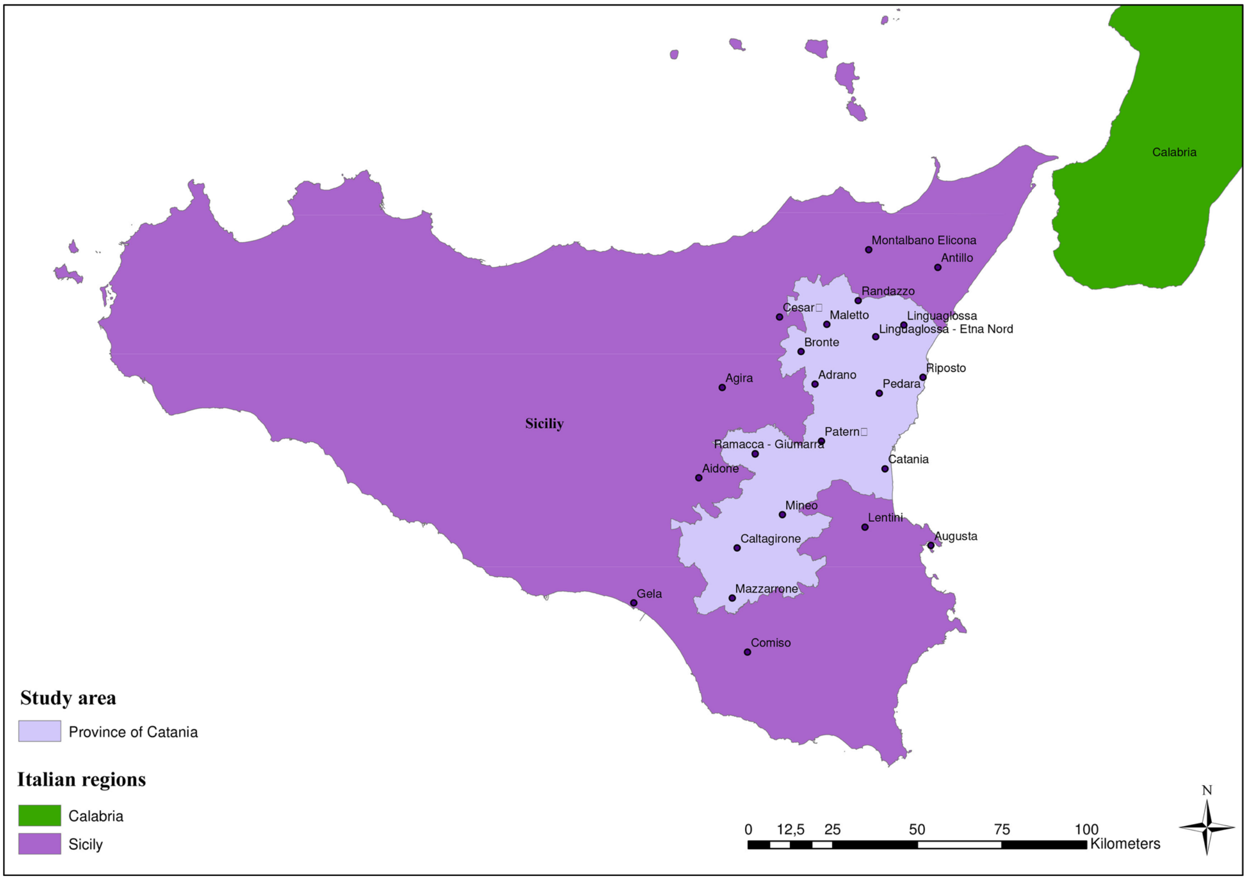

FIGURE 1 Localisation of weather stations within the study area

by assuming that 48% of the incident beams fall within the action-interval between 400 and 700 nm (Weiss & Norman, 1985).

For evaluating the clay, silt, and sand values of the soils in which weather stations are located, the following maps were taken into account for GIS analyses:

- Italian map of the clayey soils provided by the Ministry of University and Scientific and Technological Research and by the National Research Council, which was carried out based on 1985 cartography;
- The Dominant Surface Textural Class of STU map provided by the European Soil Data Center (ESDAC), https://esdac.jrc.ec.europa.eu/;
- The Topsoil physical properties for Europe map developed by the European Soil Data Center (ESDAC);
- The Harmonized World Soil Database (HWSD) (v 1.2) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

The HWSD, in particular, made it possible to define the fractions of clay, silt, and sand of topsoil, which represents the soil layer between 0- and 30-cm depth. Results of these elaborations are reported in Figure 2.

The 23 weather stations were georeferenced in GIS, as shown in Figure 1. In detail, the geographical coordinates of the weather stations were acquired and transformed into a new vector layer (point as feature). The obtained map was overlaid to the map reporting the soil types (Figure 2b), in order to define their soil texture.

On this basis, for each selected soil texture associated to the weather stations, the soil water content was computed, according to Saxton et al. (1986), by setting the soil water potential equal to $\Psi_s = 0.5$ MPa. By assuming that each soil can be defined through the parameter g_i as a function of the soil water content when $\Psi_s = -0.5$ MPa and, by considering a linear relationship between Ψ_s and precipitation (Nobel, 1988; Nobel et al., 1987), each type of soil was compared to the rainfall R (mm) and duration (in days), and only when Ψ_s exceeded the values of −0.5 MPa, the types of soil were also compared to the behavior of sandy soils as defined by Nobel and Venezuela (1987).

The point data, defined as EPI_{annual} and computed for each weather station, were then interpolated by using, among the stochastic methods, the *Kriging* tool, available in GIS software, in order to determine the EPI_{annual} value over the whole study area.

In this regard, as reported in the literature, it has been observed that when the amount of acquired data results high,

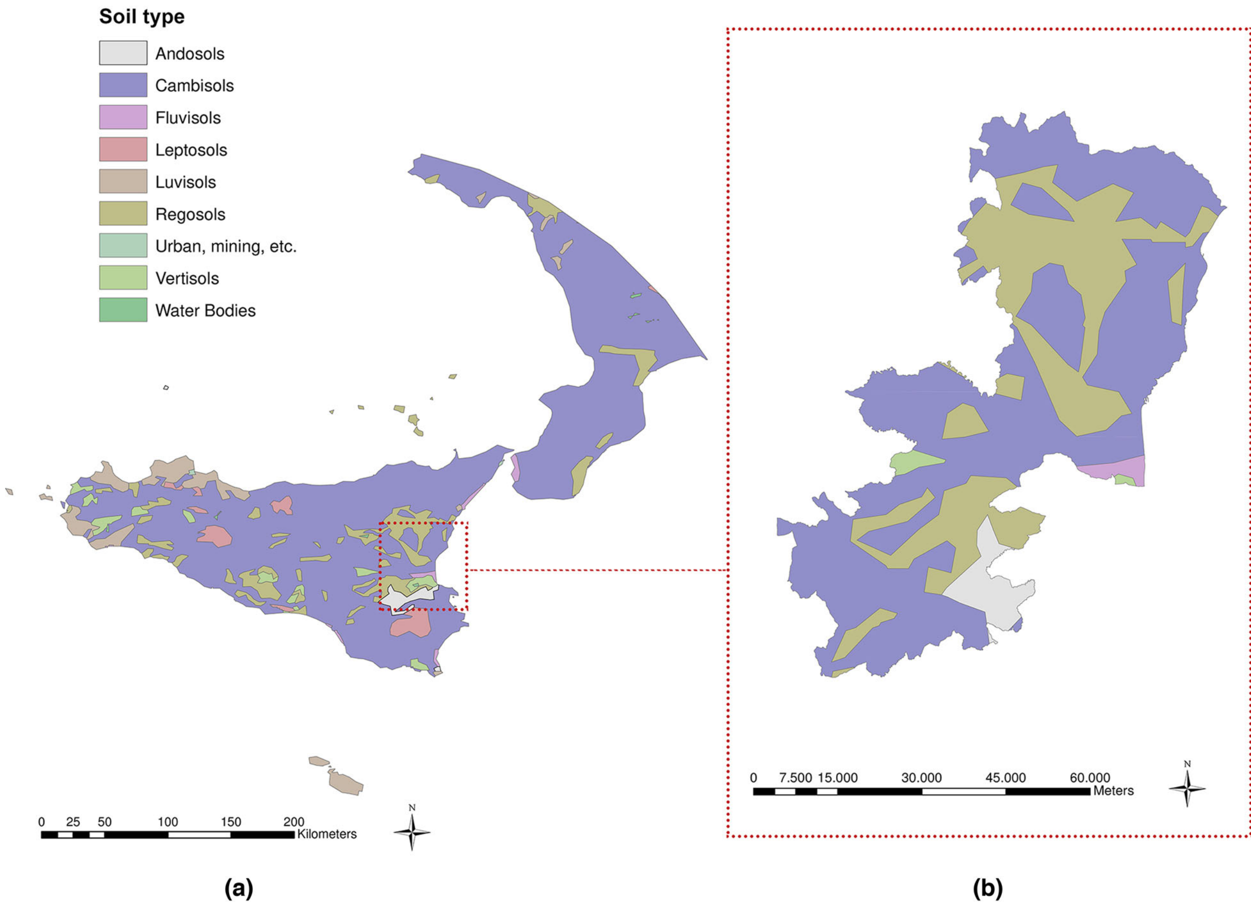

FIGURE 2 Soil type distribution based on Harmonized World Soil Database (HWSD). (a) Distribution at regional level within Sicily region. (b) Distribution at provincial level within the study area (i.e., Catania province)

and with a well distribution over the territorial areas, all methods, both deterministic ones (i.e., IDW, spline) and stochastic ones (i.e., kriging and co-kriging), of spatial estimation and analysis result acceptable. On the contrary, only in the case of complex morpho-topographic characteristics, with low data acquired due to the number of weather stations, stochastic methods for minimizing the possible estimation errors should be applied (Fiorenzo et al., 2008).

The monthly values of the I_w, I_t, and I_p indices were computed over a 10-yr period (2006–2015) and reported in ArcGIS to produce the map of the EPI distribution within the study area.

Then, by means of the *Kriging* tool, the interpolation of the monthly indices was carried out, producing 12 maps, for each considered indicator ($I_{w\_gen}, I_{w\_feb}, \ldots, I_{w\_dic}; I_{t\_gen}, I_{t\_feb}, \ldots, I_{t\_dic}; I_{p\_gen}, I_{p\_feb}, \ldots, I_{p\_dic}$).

Next steps involved the use of the ArcGIS *map algebra tool* to compute the monthly EPI, related to each month of the year (i.e., $EPI_{\_January}$; $EPI_{\_February}$; $EPI_{\_March}$, etc.) and then the computation of annual EPI, according to Equation 1.

The raster file of EPI distribution was then firstly converted into weighted points with values ranging between 0 and 1, based on the index, and then overlaid with municipality boundaries of the Province of Catania. In detail, the vector layer contained polygons that represent the surface area of each municipality.

As a result, for each municipality a new layer was defined containing both the weighted points with values ranging between 0 and 1, and the adopted EPI weights with the aim of computing for each municipality, the average EPI value.

Finally, the EPI_{annual} index was applied to compute, per year and per hectare, the potential production of biogas, by adopting the value that represents the maximum dry biomass productivity (PBp), according to Equation 13.

4 | RESULTS AND DISCUSSION

4.1 | Environmental productivity index

Nine different soil types were found in the study area, that is, Etna volcanic cone, alluvional plains, coastal plains, arenaceous reliefs, carbonate reliefs of the Hyblaean hill,

TABLE 2 WGS84 geographical coordinates of the weather stations and related provinces

Meteorological station	Longitude	Latitude	Provinces of Sicily
Linguaglossa	15.034649	37.790359	Catania
Ramacca	14.63355	37.48101	Catania
Caltagirone	14.57481	37.230025	Catania
Randazzo	14.97775	37.88973	Catania
Pedara	15.048439	37.642643	Catania
Paternò	14.855254	37.514767	Catania
Mineo	14.725331	37.319229	Catania
Mazzarrone	14.559542	37.096146	Catania
Maletto	14.872486	37.826202	Catania
Linguaglossa	15.130906	37.824482	Catania
Riposto	15.198342	37.685127	Catania
Catania	15.067711	37.441788	Catania
Adrano	14.833333	37.666667	Catania
Bronte	14.786194	37.753529	Catania
Gela	14.231500	37.081400	Caltanissetta
Aidone	14.446100	37.416500	Enna
Cesarò	14.713900	37.845800	Messina
Lentini	15.000400	37.286500	Syracuse
Montalbano Elicona	15.013500	38.025700	Messina
Agira	14.522400	37.657200	Enna
Comiso	14.611000	36.952400	Ragusa
Augusta	15.220500	37.237600	Syracuse
Antillo	14.245600	37.978300	Messina

clayey-marly hilly reliefs, hilly reliefs with chalky or carbonate crests, hilly reliefs with sandy hills at the summit, and Hyblaean Vulcanites. In terms of soil texture, 65% of the considered 23 weather stations falls on soil classified as loam, 30% on sandy loam soil, 5% on loamy sand soil. Within these considered soil types, the percentage content of clay ranged from a minimum of about 6% in the loamy sand soils in the weather station located in Bronte municipality, to a maximum of 26% for the loam soils recorded for the weather station of Ramacca municipality. Conversely, the sand content ranged from a minimum value of 32% in the loam soils to a maximum value of 83% in the loamy sand soils (i.e., Bronte municipality).

The soil water potential had an average value of water content equal to 1,077.21 mm at $\Psi_s = -0.5$ MPa and increased in soils characterized by a lower clay content. The minimum value of 79.18 mm was measured in Bronte municipality (i.e., loamy sand soil) whereas the maximum value equal to 3,282.26 mm in the municipality of Ramacca (i.e., loamy soil). Furthermore, in Bronte municipality the minimum value of g_i, equal to 0.3370 was recorded, whereas the maximum g_i value equal to 0.6545 was found in Ramacca. Therefore, based on data elaboration, the highest value of the g_i was found in the loamy soils, that is, in the municipalities of Ramacca, Caltagirone, Mineo, Maletto, Linguaglossa, Riposto, and Adrano.

Furthermore, it emerged that, within all the territorial areas in which the weather stations are located, the I_w index resulted equal to 1 during the months of January, February, March, October, and December, in some years also in April (i.e., 2012, 2013), in September (i.e., 2009, 2010, 2011), and in November (i.e., 2007, 2009, 2011).

Conversely, this index I_w assumed a value equal to zero, in most of the territorial areas in which the weather stations are located, in the months of June (during the years 2012 and 2013), July in the year 2011, and August (during the years 2011 and 2014). Therefore, the wettest municipality was Linguaglossa and the driest Ramacca.

During the calculation of the I_p index, the value of $I_p = 1$ was always found during the entire time interval (i.e., 10 yr) in the months of April, May, June, July, August, and September, and only for the years 2012 and 2015 also during the month of March. The value of $I_p < 1$ was found in the months of March and September only for the weather station located in the municipality of Pedara. The minimum PAR value of 5.06 mol m $^{-2}$ day^{-1} was registered for the year 2011 during the month of November in the weather station located in Pedara municipality whereas the maximum value of 29.01 mol m $^{-2}$ day^{-1} was found during the month of June in the weather station located in Gela municipality, which is a weather station located outside the provincial administrative boundaries.

The results of the I_t computation showed values between −0.75 and 1 as minimum and maximum values, respectively. During the interval April–October and for some years also during the month of November, higher average values of the I_T were found. Therefore, it was observed that *OFI* showed higher values of CO_2 potential absorption at different daily T_{max} values (Owen & Griffiths, 2014). In general, a low night temperature and the resistance to variations in temperatures between day and night demonstrated that the species has a greater suitability in southern latitudes as characterized by these considerable variations in temperature within the same season (Owen et al., 2016). The lowest average value for the minimum temperature was found in the weather station located on the Etna volcano, while the highest average value for the minimum temperature was found in the municipality of Ramacca, which is located at 270 m asl and at about 45 km-distance from the coast. The lowest average value for the maximum temperature was found in Maletto municipality (960 asl on the Northwest side of the Etna volcano) while the highest one was recorded in the municipality of Paternò (225 m asl, at 18 km distance from the coast).

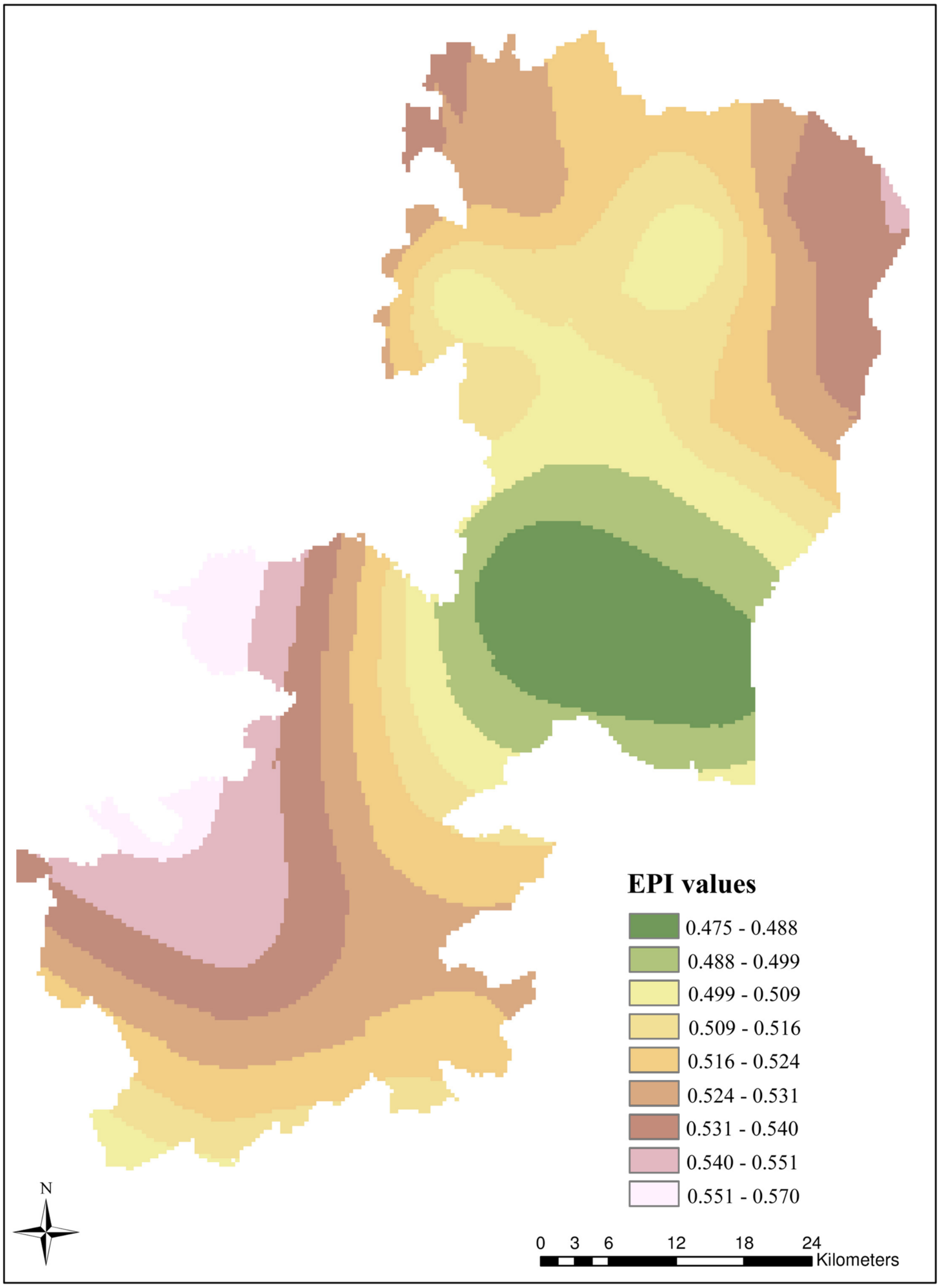

FIGURE 3 Environmental productivity index (EPI) yearly value distribution within the whole province of Catania

Recorded data were elaborated and reported in the GIS software to produce the EPI map. Figure 3 shows the index distribution at the territorial level within the whole province of Catania where EPI values ranged between 0.47 and 0.57. Therefore, the maximum EPI value was <0.60 as found by Owen and Griffiths (2014).

The most suited areas for *OFI* were found in the Southwest (currently the commercial production area of *OFI*), in the northeastern and northwestern areas of the province, and also in those territorial areas close to the administrative boundaries between the provinces of Catania and Messina. In detail, the municipalities of Mirabella Imbaccari, Raddusa, San Cono, Mineo, Grammichele, Calatabiano, Fiumefreddo, Caltagirone, Castel di Iudica, Piedimonte, Mascali, Giarre, Santa Venerina, and Maniace were selected as the most suitable areas.

On the contrary, the area of the Catania plain, the area at the top of the volcano, and the area located to the Southeast close to the administrative boundaries between the provinces of Catania and Ragusa, were identified with a low suitability value. In detail, the municipalities of Catania, Misterbianco, Paternò, Belpasso, Camporotondo, Tremestieri

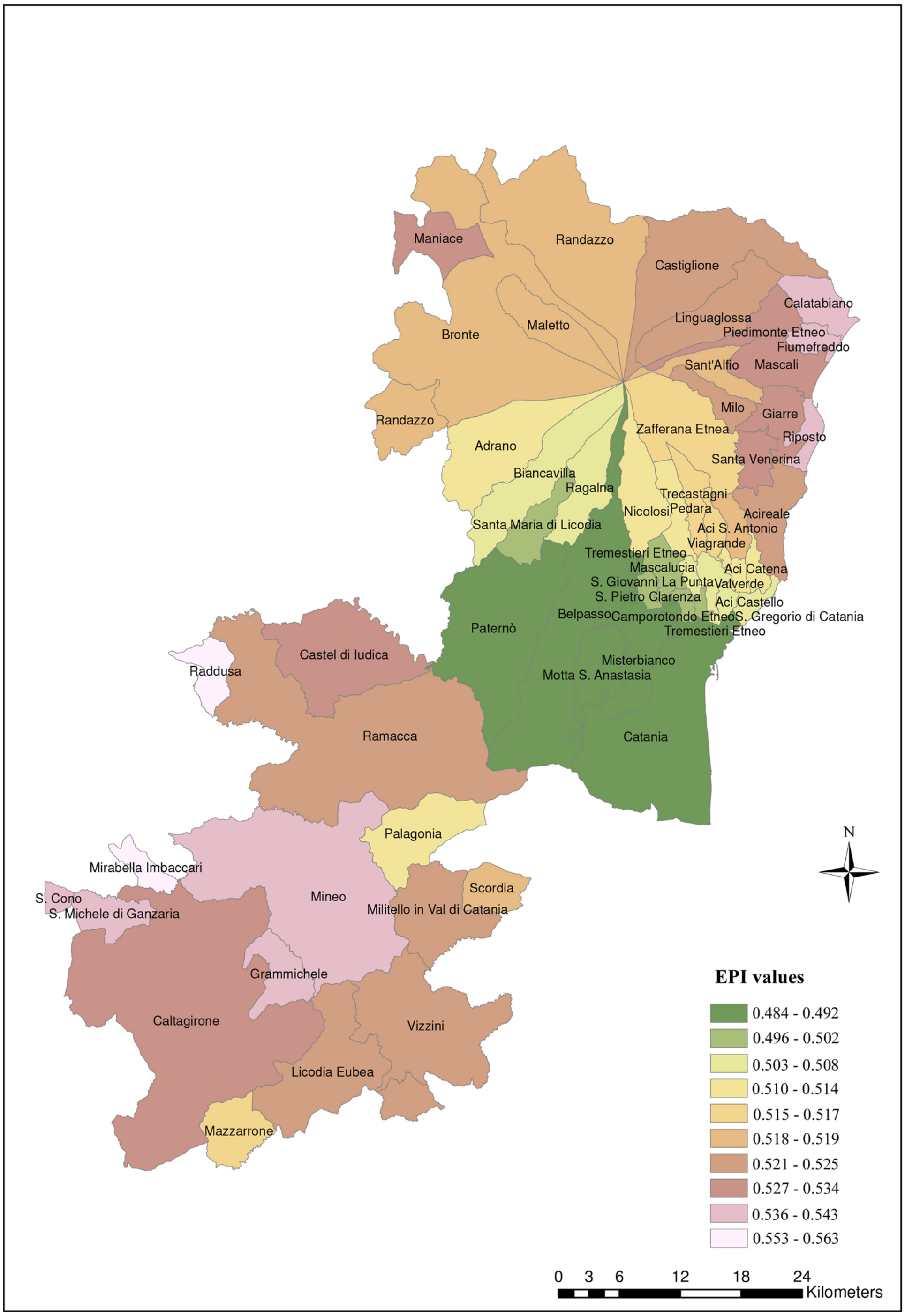

FIGURE 4 Environmental productivity index (EPI) yearly value distribution within the municipalities of Catania province

Etneo, Mascalucia, and Santa Maria di Licodia were selected as the less suitable areas.

The municipalities with a high EPI value were found to have an average monthly rainfall ranging between 40.00 and 80.00 mm. These values are rather moderate in comparison to those recorded in the other municipalities and contribute, together with the soil characteristics (i.e., high value of g_i), to reach a high value of I_w indicator during the EPI calculation. Conversely, high rainfall that will theoretically raise the EPI value would not produce high yields of *OFI* within the considered territorial areas, because they are characterized by sandy loam or loamy sand soils and therefore low I_w values. As regard to soils with a high clay content, that provides low values of water absorption, these do not contribute for reaching optimal EPI values. In this regard, it has been found that soil texture and rainfall are the main factors affecting the

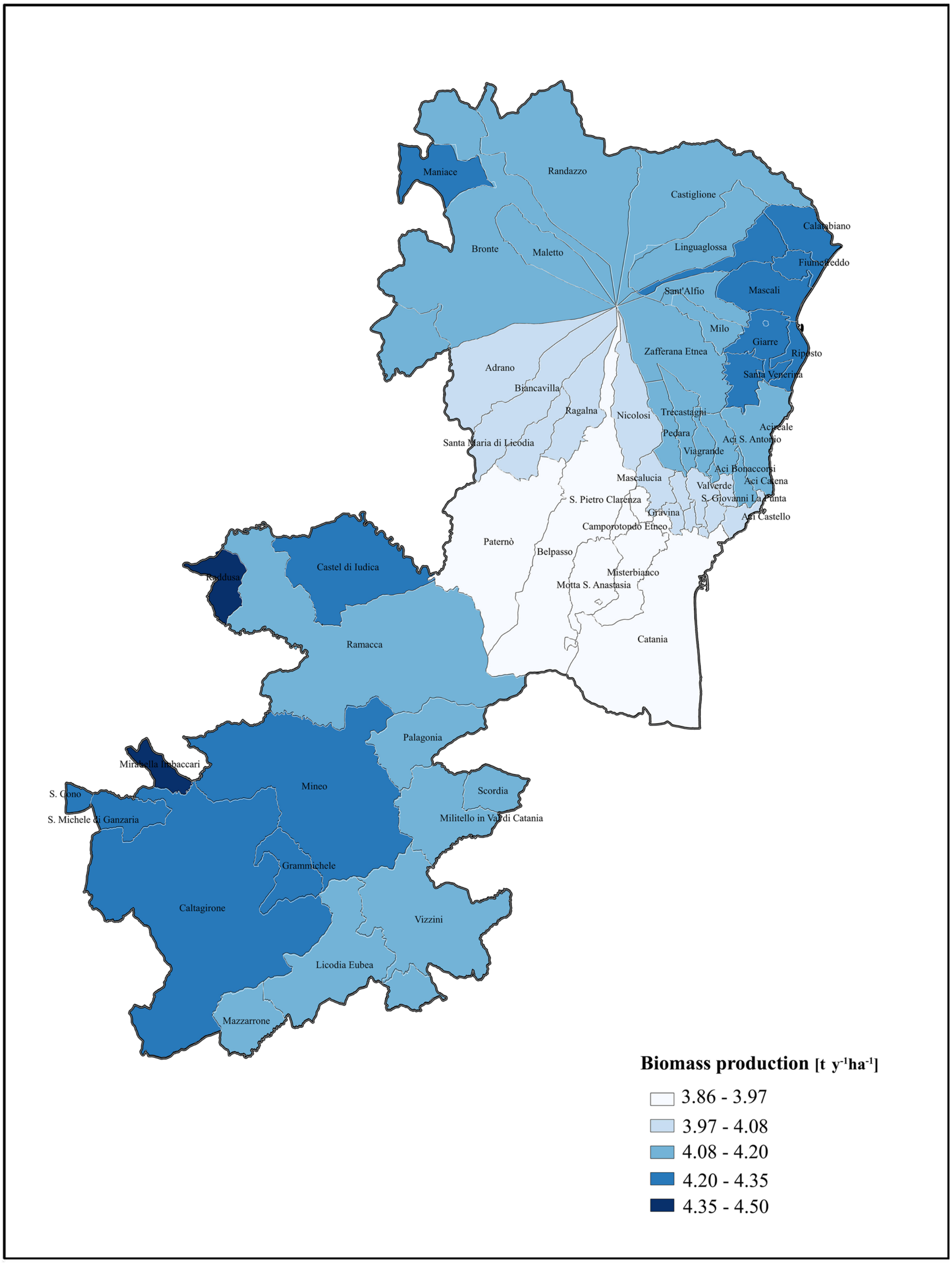

FIGURE 5 Distribution of the potential biomass production computed per hectare

productivity of *OFI* (Guevara & Estevez, 2001). In a previous study (Leanza et al., 2022), also the maximum temperature and the altitude were relevant factors for the estimation of *OFI* probability of presence.

Within the most suitable municipalities, the monthly average values of the minimum temperatures were the highest, whereas the average values of the maximum temperatures were found similar to those registered for the other municipalities of the province. This latter result, found for the maximum temperatures, applies also for the monthly average value of the PAR that, in the most suitable municipalities, was recorded as being equal to 16.80 mol m $^{-2}$ day^{-1}, which is a value close

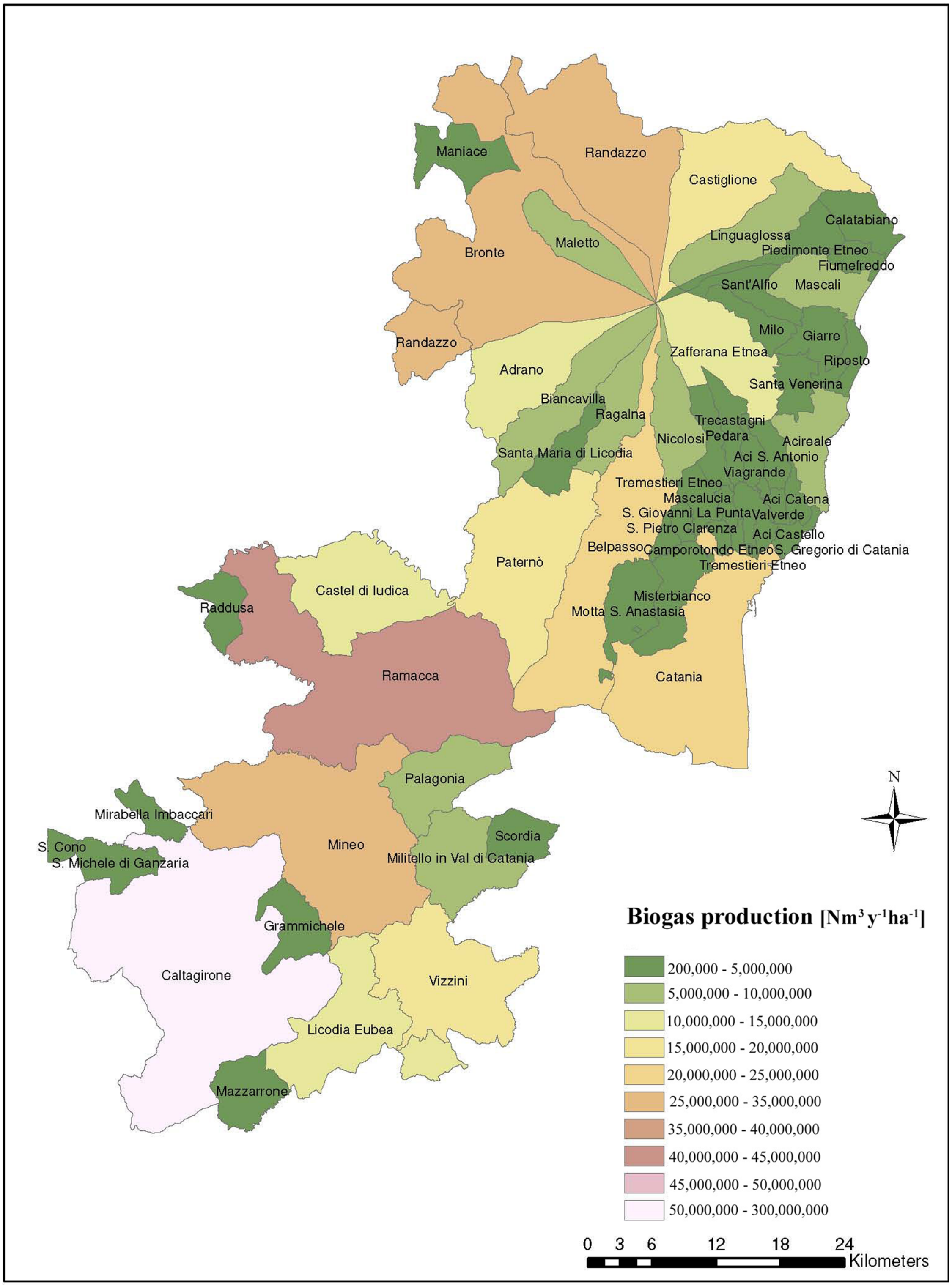

FIGURE 6 Distribution of potential biogas production in the municipalities of Catania province

to those registered in the other municipalities of the province. Therefore, it is possible to highlight that the minimum average temperature affects the carbon absorption, unlike the maximum average temperature and the PAR.

By analyzing other research studies carried out in Sicily (Comparetti et al., 2017), it was observed that this region could be highly exploited for agro-energy crops, especially for the cultivation of *OFI*, in marginal areas currently not

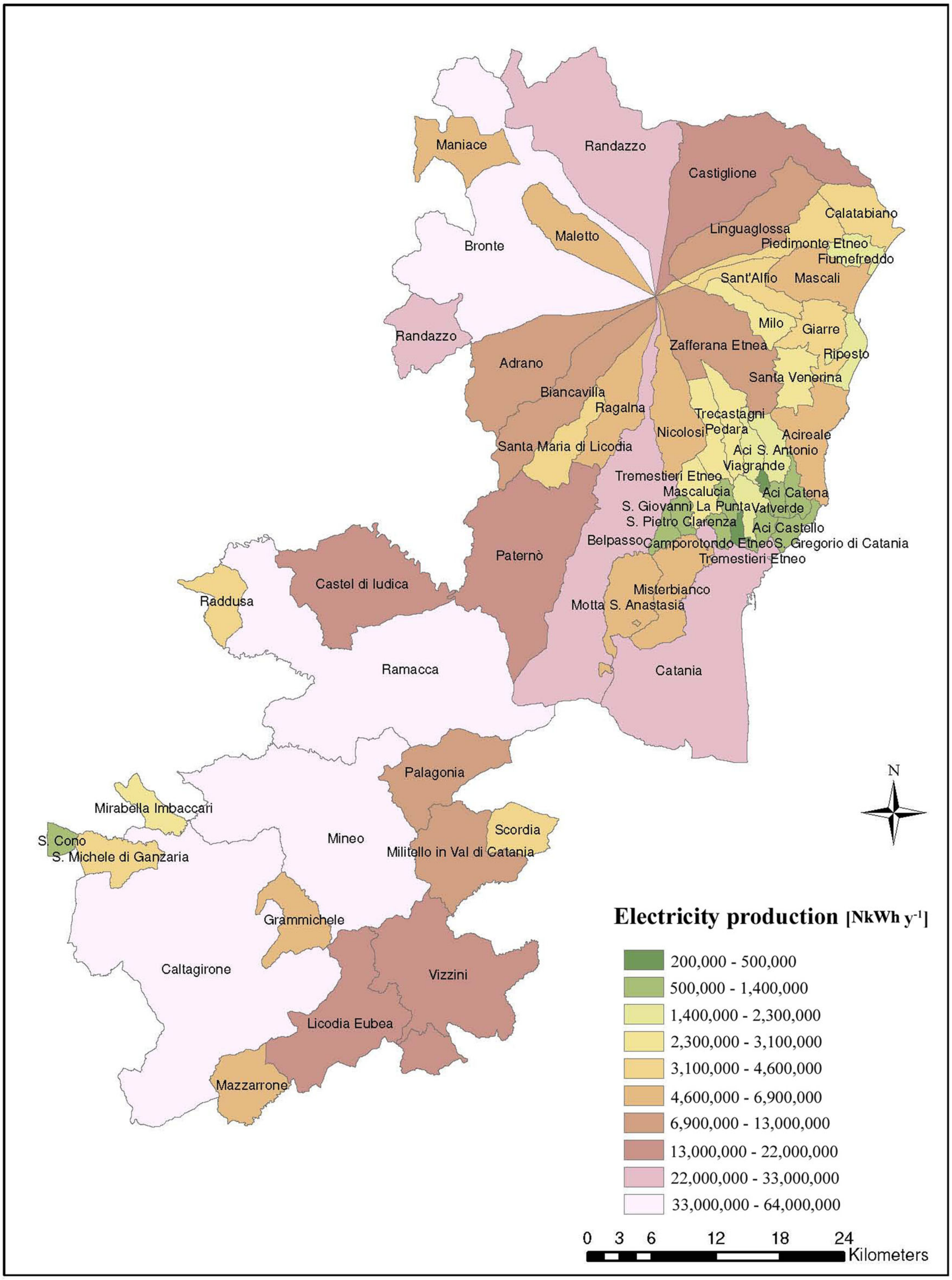

FIGURE 7 Distribution of potential electricity production per year and hectare

dedicated to cultivation. Those areas considered marginal are where agricultural use has lowered due to various issues, such as population decrease, reduction of agricultural employment, reduced services, and degraded areas. In detail, in these areas, cultivation can reach about 600,000 ha (ISTAT, 2011), at an altitude lower than 700 m a.s.l., with a temperature that rarely drops below 0 ˚C, and a slope ranging between 5 and 35% (Comparetti et al., 2017). These results are in line with those acquired in a previous research (Leanza et al., 2022) where good potential for *OFI* presence was found in hilly territories, having an altitude ranging from approximately 200–600 m.

By considering the computed values of the EPI, it is possible to evaluate the productivity of potential biomass and therefore a better estimation of the amount of biogas potential production.

In Figure 4, the average value of the EPI provides an estimation of the index per square meter of surface area in each municipality.

4.2 | Potential biogas and electricity production within the study area

The potential biomass production was computed per hectare for each municipality and its distribution was reported in Figure 5. The municipality with the lowest production of biomass was Motta Sant'Anastasia (3.86 t yr^{-1} ha^{-1}) followed by the municipalities of Misterbianco, Paternò, Catania, Belpasso, and Camporotondo Etneo, which are mostly located within the inner areas of the province (i.e., Catania plain). Low values of biomass production per hectare were also found in those municipalities situated on the slopes of Etna volcano. In detail, territorial areas located in the southern area of the volcano resulted less suitable than those located in the northern area.

The outcomes of the analyses proved that the soils located close to the Caltagirone municipality were found as the most suitable ones. In detail, the municipality of Raddusa registered the highest biomass production per hectare, equal to 4.50 t yr^{-1} ha^{-1}, followed by the municipalities of Mirabella Imbaccari, San Michele di Ganzaria, Grammichele, San Cono, and Mineo. With regard to the municipalities belonging to the Ionian coast, Giarre, Calatabiano, Fiumefreddo, Riposto, and Mascali resulted in the most suitable ones.

In Figure 6, the distribution of the potential biogas produced was reported for the province of Catania. It was computed by taking into account and combining the EPI values and data from the literature on the potential biomass production and its capacity to produce biogas. Municipalities were classified by using the method that adopts the data division into predefined groups, which are established prior to data classification. This classification method was used for showing both the biogas potential biogas and the electricity distribution at territorial level (Figures 6 and 7). In detail, Figure 6 shows that the Caltagirone municipality represents the best territorial area for an excellent potential biogas production, followed by the municipalities of Ramacca, Mineo, Randazzo, and Bronte.

According to the last step of the methodology reported in this study, the potential biogas production and electricity production per hectare were evaluated to be 1,240.99 Nm^3 yr^{-1} ha^{-1} and 1,551.24 kWh yr^{-1}, respectively, based on a computed average biomass production from *OFI* equal to 4.14 t yr^{-1} ha^{-1} (Figures 6 and 7)

These results are in line with those obtained by Comparetti et al. (2017). In detail, in their research study, a biomass production equal to 2,500 (10^3 t), biogas production of 87,500 (10^3 m^3), biomethane production of about 49,000 (10^3 m^3), electricity production of 9,583 (MWh), and thermal energy production of 10.062 (MWh) were computed for the province of Catania. Therefore, the results reported by Comparetti et al. (2017) applied to an area of 600,000 ha, as in this study, would produce an estimation of the average biomass production from *OFI* equal to 4.17 t yr^{-1} ha^{-1}, close to that obtained in this study, thus confirming the suitability of the methodology.

5 | CONCLUSIONS

In this study, the objectives aimed at defining the potential biomass production of *OFI*, its theoretical potential production of biogas, and therefore the potential electricity production were achieved by applying tailored indices, based on local values of climate variables and geospatial analyses. The use of GIS software allowed the visualization at the territorial level of bioclimatic data recorded by 23 selected weather stations within the study area, during a 10-yr time interval, the elaboration of the acquired data by spatial analysis tools, and the computation of the EPI. In addition, the results achieved from GIS analyses, allowed the identification of the most suitable territorial areas for producing biogas from *OFI*, and an estimation of electricity production per year and per hectare. Based on the outcomes, the combination of the methodology and tools, applied at the territorial level, allowed increase of knowledge on the use of the *OFI* biomass residues for a sustainable production of both electricity and biogas in the Mediterranean area. Further studies could be focused on coupling the results of potential biomass production with geostatistical analyses of species presence based on various predictors.

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AUTHOR CONTRIBUTIONS

Paola Maria Leanza: Software; Validation. Francesca Valenti: Data curation; Visualization; Writing – original draft; Writing – review & editing. Provvidenza Rita D'Urso: Writing – review & editing. Claudia Arcidiacono: Conceptualization; Supervision; Writing – review & editing.

CONFLICT OF 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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