

1 *Research paper*

2 **A Compendium of Findings and Experiences on** 3 **Reusing Agro-industrial By-products for a** 4 **Sustainable Biogas Production in a Region of** 5 **Mediterranean Basin**

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11
12 **Abstract:** The necessity to investigate suitable alternatives to conventional fossil fuels has
13 developed the interests in many renewable energy alternatives, especially biomass resources which
14 are widely available and allow to reach both environmental and socio-economic improvements.
15 Among the bioenergy solutions the anaerobic digestion technology **makes it possible** to produce
16 biogas by reusing and valorising agricultural residues and by-products.

17 In Southern Italy, to date, the development of biogas sector is still very limited, despite the
18 importance of the agricultural sector, especially of citrus and olive cultivation. For this reason, **in**
19 **previous studies** the availability of two by-products, i.e., citrus pulp and olive pomace, was analysed
20 in order to choose the most suitable area **for a sustainable development of new biogas plants**
21 **according to the new Biogasdoneright concept.** **In this paper,** **after a resume of the multi-step**
22 **methodology which allowed the computation of biogas production,** it was demonstrated that 15.9
23 GWh-e electricity and 24.5 GWh-e heat per year could be generate by reusing only these two kind of
24 by-products, and could satisfy approximate 17% of the total electricity demand of the agricultural
25 sector (90.2 GWh-e/year) in Catania.

26
27 **Keywords:** by-products; biogas; BIOGASDONERIGHT; citrus pulp; olive pomace; GIS; indicators;
28 biomass availability.
29

30 **1. Introduction**

31 Rapid acceleration of industrialization combined with the increase of the population and
32 expanding urbanization, has dramatically changed our world. Signs of climate change rise concerns
33 for the future of the planet [1]. Emissions of carbon dioxide have increased by more than 80% since
34 the early 70's, mainly due to the increase in consumption of fossil fuels [2] and changes in land use
35 [3, 4]. The 2015 United Nations Climate Change Conference (officially known as Conference of the
36 Parties COP 21) concluded the Paris Agreement [5], a global agreement on the reduction of climate
37 change, in which global warming is set at the increase of less than 2 degrees Celsius (°C) compared
38 to pre-industrial levels and the **CO₂** emissions reduction of 50% by year 2050. 85% of current energy
39 consumption is based on fossil fuels, which is the most responsible source for greenhouse gas (GHG)
40 emissions.

41 According to the estimated world energy requirement, the energy demand would increase
42 approximately 36% between 2008 and 2035 [6]. To sustainably satisfy this demand, renewable energy
43 technologies must be implemented to balance and reduce fossil energy use.

44 A suitable alternative to conventional fossil fuels in terms of environmental impact reduction
45 according to the Kyoto protocol [7, 8] is represented by renewable energy sources because they could
46 significantly contribute to reduce the CO₂ and other GHG emissions [9].

47 Many renewable energy alternatives (i.e., solar, wind, hydro, geothermal, and biomass) have
48 been widely studied and, by considering cost effectiveness, practicability, scalability, positive
49 externalities and energy density, bioenergy from biomass often offers a versatile and realistic
50 solution, particularly for rural communities where massive quantities of agricultural biomass and
51 residues are produced [10].

52 Biomass resources have been acquiring particular interest in recent years because they are
53 widely available and allow the production of bioenergy at reasonable prices. Moreover, biomass
54 resources valorisation can trigger environmental and socio-economic improvement such as crop
55 diversification, greenhouse emission reduction and creation of new jobs [9, 11].

56 Recently, among the technological solutions for bioenergy production, the anaerobic digestion
57 (AD) technology to treat agricultural wastes and biomass for biogas production, was widely
58 investigated [12, 13]. In this regard, many studies have been conducted to improve digestion
59 efficiency and enhance its economic performance, such as designing of new reactor configurations to
60 better digest different feedstocks [14], or running co-digestion to improve biogas production [15], or
61 upgrading raw biogas to high-quality fuels [16].

62 With advancements in the application of ICT in agriculture research field, geographical
63 information system (GIS) tools has been intensively used to carry out in-depth analyses of feedstock
64 supply and logistics for biogas production around the world, and to provide decision support
65 information for establishing biogas production systems at local, regional, and national levels [17, 18].
66 In this context, GIS tools have been considered appropriate for spatially-related issues [19-22] and
67 have been applied for assessing the potential biomasses for biogas production [23-25] and for site-
68 location analysis [26-33].

69 While the spread of biogas plants has earlier and continuously increased in Europe, it is more
70 recent in Italy: the sector started growing since the beginning of the new century, registered a very
71 high development after 2009, when the TO (omni-comprehensive tariff) including a high energy price
72 and a financial incentive came into force. The number of biogas plan quickly increased to 989 in three
73 years with an overall installed power of approximately 770 megawatts at the end of 2012. In the TO
74 period (2008-2012), biogas plants have mostly spread in the livestock farms of Northern Italy, with
75 the objective of obtaining methane from animal wastes for energy purposes.

76 But, in many regions within the North-Central Italy, the biogas is produced by using dedicated
77 energy crops (e.g., beetroot, sugar cane, sorghum, and corn and wheat), due to their adaptability to
78 soil and climatic unfavourable conditions, enhancing thus the marginal areas or abandoned areas of
79 agricultural land [34]. Unfortunately, producing biogas by using dedicated energy crops arises
80 environmental, social and economic concerns related to food vs. fuel competition [35]. As a
81 consequence, there is the need to analyse the possibility of using alternative biomass sources (non-
82 food sources) for the production of methane by anaerobic digestion [36]. Therefore, a new concept to
83 produce biogas, integrating sustainable intensification of crop rotation and the use of agro-industrial
84 wastes, known as Biogasdoneright was developed [37-39]. The adoption of this new system of
85 production would reduce the environmental, economic and social impacts related with the
86 cultivation of dedicated energy crops and the presence of waste generated by agro-industrial
87 activities [40].

88 To date, the development of biogas plants in Sicily, which is the largest island in the
89 Mediterranean basin, is still very limited, despite the importance of the agricultural sector for the
90 island. For this reason, after a resume of the multi-step methodology which allowed the computation
91 of the potential biogas production from anaerobic digestion of two by-products, i.e., citrus pulp and
92 olive pomace [21, 41-43], in this study electricity and heat production from the obtainable biogas was

93 computed in order to highlight how a sustainable valorisation of the considered by-products could
 94 partially solve energy demand of the agricultural sector.

95 2. Materials and Methods

96 2.1 Study area

97 2.1.1 Improving the biogas sector in Sicily

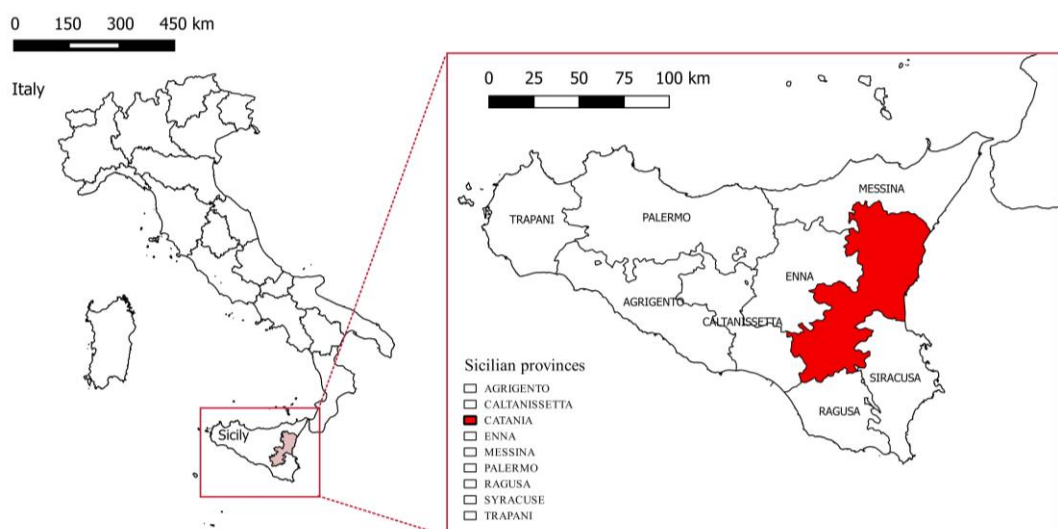
98 Sicily is a Region of the Southern Italy composed of 9 provinces (figure 1). The surface of the
 99 island has a complex and irregular morphology. Almost two-thirds (61.4%) of the island is hilly and
 100 a quarter (24.5%) is mountainous.

101 In Sicily, as well as in the rest of Southern Italy, the agricultural sector has a key role, in fact,
 102 according to official statistics Sicily is the region with the greatest extension of agricultural land,
 103 where agriculture has been one of the major economic resources due to the quality and wide variety
 104 of products. By considering the surface area dedicated to agriculture, Sicily leads in cereal production
 105 and orange production (52% of the entire national production) [44]. ISTAT [45] data indicate that
 106 Sicily is one of the regions in Italy with highest concentration of growing areas, which equals about
 107 231 thousand hectares. Furthermore, just considering the Sicilian agricultural sector, the main plants
 108 are olive and citrus cultivation, which represent 90% of the total cultivations in Sicily.

109 Moreover, the unique weather conditions (mild/wet winter and hot/dry summer) make Sicily a
 110 region with a great potential for renewable energy production. In detail, renewable energy (4,709
 111 GWh/year) provided approximately 25% of total power generation in Sicily in 2013 [46], where wind
 112 and solar power were the dominant renewable energy sources.

113 By considering the extensive and intensive farming and food processing operations in Sicily, it
 114 is evident that biomasses such as by-products, i.e. citrus pulp and olive pomace, are not frequently
 115 used for renewable energy production. In fact, only around 70 GWh is provided to the agricultural
 116 sector from the bioenergy sector.

117



118

119 **Figure 1.** Geographical position of Sicily (Italy)

120 2.1.2 Citrus and olive cultivations, processing industries and the related by-products

121 Citrus production is relevant in Italy, since it covers an area of 142,011 ha with a production of
 122 2.7 million tons, according to recent statistical data.

123 Data gathered from the 2010 Agricultural Census highlighted that approximately half (46%) of
 124 citrus farms are located in Sicily whereas the other Regions have no more than 8%, except for Calabria
 125 at 26% [47, 48].

126 There are about 79,500 citrus farms in Italy, which are mostly located in Sicily and Calabria
 127 (72%). As regard the Sicilian citrus production, it is mainly located in Eastern Sicily, especially in the
 128 provinces of Catania and Syracuse [21].

129 By considering the olive oil cultivation, this has a key role for the economy in many
 130 Mediterranean Regions, especially Spain, Italy, Greece and Portugal which produce more than 98%
 131 of the world's olive oil with an estimated value of 2.5 million metric tons/year [49, 50].

132 By analysing the situation in Italy, olive oil industry is the biggest consumer (followed by Spain
 133 and the USA), the biggest importer (followed by the USA and France), and the second most important
 134 producer and exporting country (after Spain) [49, 51].

135 Data gathered from VI Agriculture General Census 2010 [52], showed that the olive farms are
 136 mostly located in the southern regions of Italy (i.e., Apulia, Calabria and Sicily), which have the
 137 highest percentage of cultivated surface [41,53-55].

138 As regard the management of agro-industrial by-products, i.e., citrus pulp and olive pomace, is
 139 a challenge issue for the processing facilities from both economic and environmental perspectives,
 140 and their re-use as renewable energy source to produce biogas by anaerobic digestion could
 141 contribute to reduce the issues related to their management.

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144 2.2 The GIS model to estimate potential energy production

145 In previous research works a GIS-based model suitable to analyse the spatial distribution of
 146 citrus and olive producing areas and the amount of processed citrus and olive was built (table 1) in
 147 order to quantify the related by-products (i.e., olive pomace and citrus pulp) potentially available for
 148 biogas production.

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 150

Table 1. Previous research studies.

	Objective	By-products analysed	Study area
<i>Valenti et al., 2016</i>	Gis-based model development	Citrus pulp	Sicily
<i>Valenti et al., 2017b</i>	Gis-based model application	Citrus pulp	Catania province
<i>Valenti et al., 2017c</i>	Gis-based model application	Olive pomace	Catania province
<i>Valenti et al., 2017d</i>	Suitable area for biogas sector development	Citrus pulp and olive pomace	Catania province

151

152 Firstly, the GIS-based model for the estimation of citrus pulp and olive pomace potential
 153 availability for biogas production was applied at a provincial level. The model required the use of a
 154 set of indicators which was previously defined and quantified by means of suitable databases and
 155 field surveys.

156 The proposed methodology allowed the development of a spatial index icp_a , which describes
 157 the level of availability of citrus pulp for biogas production at a regional scale. In order to compute
 158 this index icp_a , several indicators i.e., P_{citrus_i} ; $P_{processed_citrus_i}$; $Cp_{average\%}$ and Cp_i , widely
 159 described by Valenti et al., [21], were computed for each n zone ($i = 1$ to n) corresponded to each
 160 province of Sicilian region, by following equations:

$$161 \quad i_{cp_a_i} = \frac{Cp_i}{Cp_{tot}} \quad (1)$$

$$162 \quad Cp_i = Cp_{average\%} \times P_{processed_citrus_i} \quad (2)$$

163

$$164 \quad Cp_{average\%} = \frac{\sum_j^m Cp_{average\%_j}}{m} \quad (3)$$

165

166 where Cp_{tot} was the amount of citrus pulp, measured in tons, produced in the whole study area,
 167 $Cp_{average\%}$ was computed for each processing industry j of the sample by the ratio between the
 168 produced citrus pulp and the amount of citrus processed, and y is the number of citrus campaigns;
 169

$$170 \quad P_{processed_citrus_i} = Ca_{citrus} \times P_{citrus_i} \quad (4)$$

171 where P_{citrus_i} quantified the average production of citrus fruits, measured in tons, within an
 172 established time interval and Ca_{citrus} was a coefficient of availability, fixed to 0.3 [47,48].

173 The computed index made it possible to describe the level of availability of citrus pulp for biogas
 174 production in a regional scale, i.e., for the Sicilian region. However, the proposed methodology
 175 exceeds application within territorial boundaries in which was tested, and could be utilized not only
 176 for the countries of the Mediterranean area, for example Portugal, Morocco, and Spain, but also for
 177 those of the Caribbean basin, such as Florida and Brazil. Brazil is, in fact, the world's largest producer
 178 of citrus fruits and the main juice exporter.

179 The model proposed by Valenti et al., [21], previously applied at regional level in Sicily, was
 180 used by Valenti et al., [41] to compute the index that describes the level of citrus pulp availability at
 181 municipal level in Catania province. The aim of this further study was to compute the theoretical
 182 biogas potential in the province. Although the information contained in 6th Agricultural Census 2010
 183 database is more accurate than that included in the ISTAT database, which was used in the previous
 184 research [21], some basic data are still missing, such as the yield of the cultivated areas. Therefore,
 185 since data about the amount of produced citrus fruits were not available at the municipal level, some
 186 preliminary elaborations were carried out before the application of the equation 4 for the computation
 187 of P_{citrus_i} , where $i = 1$ to n are the municipalities of Catania province. Firstly, the yield of citrus
 188 producing areas (Y_{citrus}) was computed at the provincial level, then it was applied to obtain the citrus
 189 production at the municipal level according to the following relation:

$$191 \quad P_{citrus_i} = Y_{citrus} \times S_{citrus_i} \quad (5)$$

192
 193 Then, the proposed GIS-based model by Valenti et al., [21] was applied until to the computation
 194 of the amount of citrus pulp potentially produced in each municipality Cp_i . Furthermore, the
 195 theoretical biogas potential associated to the estimated citrus pulp in Catania province was computed
 196 by the following relation:

$$198 \quad B_{tot} = Cp_i \times Y \quad (6)$$

199
 200 where Y is the citrus pulp biogas potential. The biogas potential (Y) was 89.3 Nm³/ttq for the
 201 feedstock material defined as "Citrus pulp of pigmented and yellow oranges sampled at the end of
 202 the whole process (extraction by means of in-line FMC juice extractors)", as reported in Cerruto et al.,
 203 [56]. At the end the obtained indicator Cp_i was reported on GIS map in order to highlight the area
 204 with the highest citrus pulp production suitable to produce biogas.

205 Since, the anaerobic digestion need a blend of different biomasses to produce biogas other by-
 206 products as suitable biomasses, i.e. olive pomace. Therefore, the GIS-based model developed by
 207 Valenti et al., [21], was adopted and applied by Valenti et al., [42], for the estimation of the amount
 208 of olive pomace potentially produced in each municipality of the province of Catania.

209 In detail, the proposed GIS-based model was adopted by considering the following
 210 indicators, P_{olive_i} ; $P_{processed_olive_i}$; $Op_{average\%}$ and Op_i .

211 Since data about the amount of produced olive were not available at the municipal level, some
 212 preliminary elaborations were carried out before the computation of P_{olive_i} , where $i = 1$ to n are the
 213 municipalities of Catania province.

214 Firstly, the yield of olive producing areas (Y_{olive}) was computed at the provincial level, then the
 215 amount of olive produced at the municipal level was computed by following the equation 7 and then
 216 it was used with data elaborated in anonymous form, coming from each industry and for each olive

217 campaign, to compute the olive pomace availability Op_i for each municipality by applying the
 218 equation 8:

$$220 \quad P_{olive_i} = Y_{olive} \times S_{olive_i} \quad (7)$$

$$221 \quad Op_i = Op_{average\%} \times P_{processed_olive_i} \quad (8)$$

222
 223 where $Op_{average\%}$ was computed for each processing industry j of the sample by the ratio
 224 between the produced olive and the amount of olive processed, and y is the number of olive
 225 campaigns, and $P_{processed_olive_i}$ was the amount of processed olive among the total amount of olive
 226 produced.

227 Then, after the computation of the amount of olive pomace potentially produced in each
 228 municipality, the theoretical biogas potential associated to the estimated olive pomace in Catania
 229 province was computed by adopting the equation 6, where the considered olive pomace biogas
 230 potential Y was 131.00 Nm³/ttq [57].

231 At the end the obtained indicator Op_i was reported on GIS map in order to highlight areas with
 232 the highest olive pomace potential production [42].

233 The last upgrade of these research studies was the assessment of the suitable area to develop
 234 biogas sector by considering both the analysed by-products, i.e., citrus pulp and olive pomace [43].
 235 The GIS-based model was applied to the municipalities of Catania province by considering both olive
 236 pomace and citrus pulp. In detail, the equations previously developed by Valenti et al., [21] were
 237 adapted for the two by-products with the aim to evaluate the biogas potential production (B_{tot_i})
 238 associated to the estimated citrus pulp Cp_i and olive pomace Op_i , and its territorial distribution.

$$240 \quad B_{tot_i} = Cp_i \times Y_{biogas_CP} + Op_i \times Y_{biogas_OP} \quad (9)$$

241
 242 A further elaboration was the categorisation of the municipalities of Catania province, based on
 243 the surface area of their territorial boundaries, by using a data clustering method designed to
 244 determine the best arrangement of values into different classes. Among the different algorithms
 245 available in QGIS software, the Jenks Natural Breaks classification method was used. After the
 246 definition of the classes, the territorial boundaries of the municipalities belonging to the classes
 247 having a density of citrus and olive growing areas higher than that of the whole province were
 248 selected to be overlaid with the feature class containing the localisation of the citrus processing
 249 industries. This operation allowed the selection of the municipalities where planning the
 250 development of new biogas plants was most suitable [43].

251 After the estimation of the theoretical biogas potential associated with the total amount of citrus
 252 pulp and olive pomace, by considering both electricity and thermal efficiencies of gas-engine CHP,
 253 the net annual electricity ($E_{Electricity}$, kWh-e/year) and heat (E_{Heat} , kWh-e) generation from biogas
 254 plant for uses outside the plant were then be calculated as follows.

$$256 \quad E_{Electricity} = B \times 50\% \times 36 \times 0.2778 \times 0.3 \times (100 - 9)\% \quad (10)$$

$$259 \quad E_{Heat} = B \times 50\% \times 36 \times 0.2778 \times 0.6 \times (100 - 30)\% \quad (11)$$

260
 261 where B is the biogas production (B , Nm³/year) obtained by considering the theoretical biogas
 262 production from literature equals to 131.00 Nm³/ton [57] for olive pomace and 89.3 Nm³/ton for citrus
 263 pulp [56]; 50% is the volumetric methane content in the biogas, 36 is the lower heating value (MJ/m³
 264 methane) of methane gas; 0.2778 is the conversion factor of MJ to kWh; 7000 is the operational hours
 265 of the gas engine in a year considering the recommended top-end overhaul maintenance for the CHP
 266 unit [58]; 9 and 30 in equations (10) and (11) above are the percentage of electricity and heat,

267 respectively, that are used internally by the biogas plants, and are thus not available for export to the
268 larger society [28]; and 0.3 and 0.6 are set as electricity and thermal efficiencies, respectively.

269 3. Results and Discussion

270 The first result obtained by Valenti et al., [21] was the computation of the spatial index icp_a , at
271 a provincial level through the equation 1. Table 2 summarizes the computed values of all the
272 indicators and the spatial index of availability of citrus pulp and, by considering citrus surfaces, citrus
273 production, and processed production data, it shows how the major provinces involved are those
274 located in the eastern coast of the island, and mainly Catania and Syracuse.

275 **Table 2.** Territorial distribution at a provincial level of the index of availability of citrus pulp
276 by Valenti et al., [21].
277

	$S_{citrus_i}^{**}$ (ha)	P_{citrus_i} (t)	Ca_{citrus}^*	$P_{processed_citrus_i}$ (t)	$Cp_{average\%}$	Cp_i (t)	icp_a
Agrigento	4,890.00	99,671	0.30	29,901.23	56%	16,708.89	0.10
Caltanissetta	172.00	1,805	0.30	541.50	56%	302.59	0.00
Catania	25,000.00	406,250	0.30	121,875.00	56%	68,104.09	0.40
Enna	2,902.00	62,275	0.30	18,682.46	56%	10,439.81	0.06
Messina	1,800.00	20,900	0.30	6,270.00	56%	3,503.69	0.02
Palermo	400.00	6,295	0.30	1,888.50	56%	1,055.30	0.01
Ragusa	2,200.00	61,500	0.30	18,450.00	56%	10,309.91	0.06
Syracuse	17,000.00	349,805	0.30	104,941.58	56%	58,641.65	0.34
Trapani	280.00	7,160	0.30	2,148.00	56%	1,200.31	0.01
Total	54,644.00	1,015,661	-	304,698.26	-	170,266.25	-

(**) Source: ISTAT.

(*) Source: INEA 2014

278 By considering the icp_a values reported in table 2, the province of Catania has the highest
279 potential production of citrus pulp. Therefore, in Valenti et al., [41] the developed GIS-based model
280 was applied to the province of Catania. By applying the equation 5, the amount of citrus fruit
281 produced in each municipality was computed and then the amount of the related citrus pulp was
282 obtained by considering equation 3 (figure 2).
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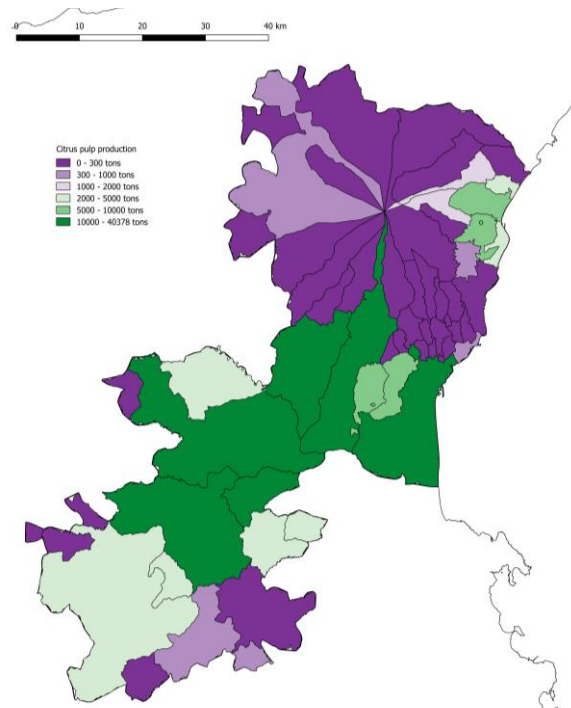
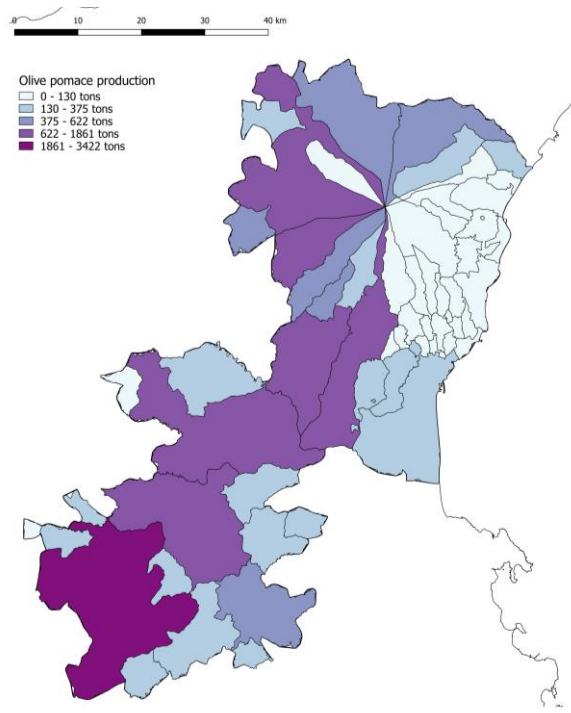


Figure 2. Territorial distribution in the municipalities of Catania province of citrus pulp indicator Cp_i .

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The province of Catania has the highest producing area of fruit tree cultivation, except for wine grapes (which are not suitable for biogas production) as reported in previous sections [41, 45]. When considering olive pomace and citrus pulp as by-products suitable for biogas production, the province of Catania is their potentially highest producing area, since it has a wide surface of citrus and olive-growing areas. Therefore, the GIS-based model developed by Valenti et al., [21], was applied with the aim of quantification the olive pomace availability. In order to highlight the areas with the highest olive pomace production the indicator Op_i , computed by applying the equation 8, was reported in a GIS map (figure 3).



298

299 **Figure 3.** Territorial distribution in the municipalities of Catania province of olive pomace
300 indicator Op_i .
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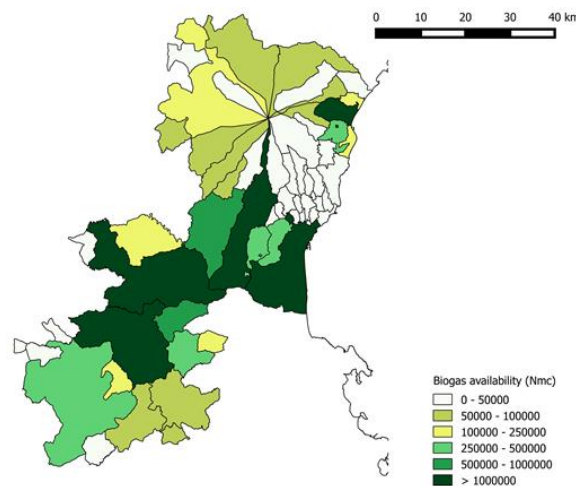
302 As shown in figure 3 the olive pomace production is more relevant in several areas of the
303 municipalities belonging to the Catania Plain district (i.e., Caltagirone, Mineo, Ramacca, Belpasso,
304 Paternò, Adrano, and Bronte), which is also the most producing area for citrus fruit.

305 In the last research study by Valenti et al., [43] the potential production of the two considered
306 by-products was computed. In fact, their quantification and localisation in Sicily could contribute to
307 build an information base suitable for multi-criteria analysis aimed at finding optimal locations for
308 developing biogas sector in a sustainable way by following the Biogasdoneright concept.

309 In order to acquire information about the amount of citrus pulp (Cp_i) and olive pomace (Op_i)
310 potentially available in each municipality of the study area, the model proposed by Valenti et al., [21]
311 was applied.

312 The amount of citrus pulp and olive pomace respectively were computed, by applying the
313 equations 3 and 8, with the aim to estimate the potential biogas availability at municipal level by
314 adopting the equation 9.

315 The potential biogas availability B_{tot_i} produced by considering only these two kind of by-
316 products was reported in GIS map (figure 4).
317



318 **Figure 4.** Estimation of biogas availability at municipal level.
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321 For the whole province of Catania, the total biogas production was estimated to be about
322 11,665,815 Nm³. In figure 4 the key role of the municipalities belonging to the Catania Plain District
323 was confirmed by the highest potential production of biogas.

324 In order to select suitable areas for the location of new biogas plants, the municipalities were
325 grouped into the five classes as reported in table 3.
326

327 **Table 3.** Classification of municipalities based on municipality
328 surface area by Valenti et al., [43].
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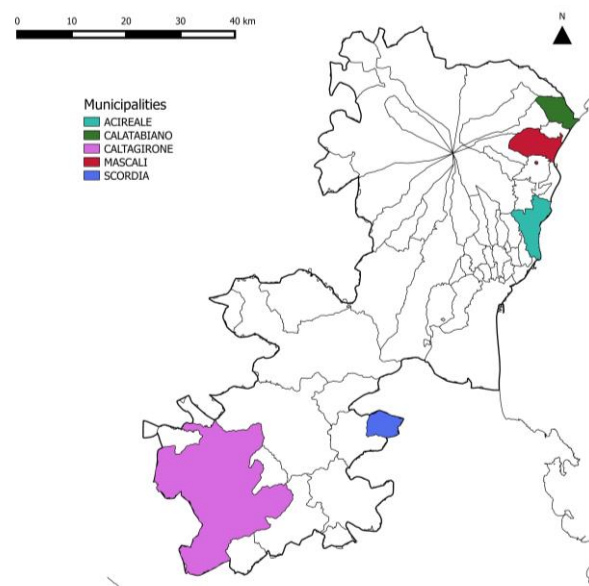
Class	S_{mun} [ha]	S_{mun_mean} [ha]	$B_{tot_i_mean}$ [Nm ³]
1st	<2414.9	1158.8	20,261.7
2nd	2414.9-6981.2	3904.3	206,169.9
3rd	6981.2-14,374.0	10,872.36	203,848.5
4th	14,374.0-24,912.4	20,900.70	737,824.6
5th	>24,912.4	34,283.19	1,308,787.4

330

331 The data analysed by Valenti et al., [43] have demonstrated that, for all the considered classes,
 332 the density variation in percentage of the citrus growing areas ranged between 5% (first and third
 333 classes) and 19% (second class) while the olive growing areas always occupied a surface area equal
 334 to about 3% of S_{mun} . Since the olive growing areas are equally distributed in percentage in all the
 335 classes, these results induce to affirm that the potential biogas production could be mainly affected
 336 by the density of the citrus growing areas, which showed to have densities higher than that of the
 337 whole province (about 10%) in the second class (about 19%), fourth class (about 12%), and fifth class
 338 (about 13%). In addition, the highest values of $B_{tot,i,mean}$ (table 3), which were found for the same
 339 classes above mentioned, drive to the same conclusion. In the GIS model the polygons of the 21
 340 municipalities belonging to these three selected classes were overlaid with the current location of the
 341 citrus processing industries (figure 5).

342 The outcomes of this analysis, showed in figure 5, have highlighted the geographical areas of
 343 the five municipalities (Acireale, Calatabiano, Caltagirone, Mascali, and Scordia) as the most suitable
 344 location for planning the sustainable development of new biogas plants with regard to the
 345 minimisation of transportation costs for feedstock supply and logistics, in terms of economic, social
 346 and environmental impacts. Among these five selected municipalities the municipality of Caltagirone
 347 was also characterised with the highest production of olive pomace and one of the most productive
 348 municipality for citrus pulp.

349



350

351 **Figure 5.** Suitable areas to locate new biogas plants in the province of Catania by Valenti et al.,
 352 [43].

353

354 Based on the quantity of biogas potentially produced by considering these two kind of by-
 355 products, i.e., citrus pulp and olive pomace, the amounts of electricity and heat generated were
 356 estimated (table 4).

357

358 **Table 4.** Electricity and heat generated by reusing citrus pulp and olive pomace for biogas
 359 production

By-products	Potential biogas production (Nm ³)	Net electricity generation (kWh-e/year)	Net heat generation (kWh-e/year)
	Caltagirone municipality		

Citrus pulp	162,464.58	221,781.89	341,202.91
Olive pomace	254,991.33	348,091.02	535,524.64
Total	417,455.91	569,872.91	876,727.55
Catania province			
Citrus pulp	9,718,056.86	13,266,208.83	20,409,552.04
Olive pomace	1,947,758.40	2,658,902.91	4,090,619.87
Total	11,665,815.26	15,925,111.74	24,500,171.91

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The potential biogas produced by considering the total amount of citrus pulp and olive pomace for the entire Catania province could be used to generate 15.9 GWh-e electricity and 24.5 GWh-e heat per year.

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The biogas electricity can satisfy approximate 17% of the total electricity demand of the agricultural sector (90.2 GWh-e/year) in Catania.

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Moreover, if considered the municipality of Caltagirone as suitable area to develop new biogas plant, it could contribute, with 0.57 GWh-e electricity and 0.88 GWh-e heat per year, which correspond to 4% of the electricity and heat produced within the 58 municipalities of Catania province by using both citrus pulp and olive pomace.

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Therefore, the valorisation of the energy potential of by-products could contribute to a more sustainable development of biogas sector, because it could both solve problems related to by-products disposal and reduce national dependence on imported fossil fuels. In detail, the issue concerning the valorisation of by-products and waste from all agro-food production is relevant also in the field of energy production from renewable energy sources. Nowadays, the sustainability of energy production is one of the main challenges for Europe. In this regard, the European Union and the Member States needed to address the challenges which derive from the high dependence on energy imports, from the scarcity of energy resources, as well as the necessity to limit climate change and overcome the economic crisis. On the one hand, the potential reduction of energy consumption and, on the other hand, the increase in energy production by using renewable energy sources could generate economic benefits for all the involved partner.

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4. Conclusions

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By considering the obtained results, through the analysed research articles, it was possible to reach step by step a more precise and detailed localisation by moving into different scale from regional to municipal level. Firstly, the GIS-based model was developed and the entire region of Sicily was select as study area by Valenti et al., [21]. As result the Catania province was chosen as most suitable area to valorise citrus pulp as by-product for biogas production, by considering the possibility to reuse it after the analysis of the actual law framework [22].

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The developed GIS-based model was then applied to the Catania province with the aim to find the most suitable area for citrus pulp production [41] and for olive pomace production [42]. The municipalities of Mineo, Ramacca, Palagonia, Paternò, Belpasso and Catania were selected for the highest potential citrus pulp produced, instead of the municipalities of Caltagirone, Mineo, Ramacca, Belpasso, Paternò, Adrano, and Bronte were selected as the most suitable municipalities for olive pomace potential production. At the end, since the anaerobic digestion need a blend of different matrices, and moreover, being these two by-products, i.e., citrus pulp and olive pomace, available only during a few months per year, it was evaluated the spatial availability of both citrus pulp and olive pomace within the Catania province and the associate theoretical potential biogas production [43]. In this context, it was demonstrated that the potential biogas production could be mainly affected by the density of the citrus growing areas, and as reported by Valenti et al., [43] the municipalities of Acireale, Calatabiano, Caltagirone, Mascali, and Scordia were selected among the municipalities of Catania province, as suitable areas for planning the sustainable development of new biogas plants with regard to the minimisation of transportation costs for feedstock supply and

402 logistics, in terms of economic, social and environmental impacts. Among these municipalities, that
403 one of Caltagirone, it was demonstrated to be characterised by the highest concentration of both the
404 two by-products.

405 On the basis of the biogas potential estimated the potential energy production was computed.
406 It was demonstrated as it is possible generate 15.9 GWh-e electricity and 24.5 GWh-e heat per year
407 which could satisfy approximate 17% of the total electricity demand of the agricultural sector (90.2
408 GWh-e/year) in Catania province, by considering only these two kind of by-products.

409 Information on other biomasses required for the anaerobic digestion within each municipality
410 of the considered classes could be useful for a more precise localisation of new biogas plants based
411 on their potential availability.

412 If local authorities would promote the application of the methodology described in this study to
413 different typologies of biomasses, it would be possible to identify the most suitable areas for the
414 localization of new biogas/biomethane plants that would properly exploit the different local by-
415 products of agriculture and animal housing.

416 Based on the actual legal framework, the achieved results could help the development of biogas
417 sector in a sustainable way by solving problems related to by-products disposal and reducing
418 environmental and economic concern related to the national dependence on imported fossil fuels.

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