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A GIS-Based Model to Assess the Potential of Wastewater Treatment Plants for Enhancing Bioenergy Production within the Context of the Water–Energy Nexus

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Abstract: The necessity of developing renewable energy sources has contributed to increasing interest in developing the anaerobic digestion for producing biomethane since it both provides green energy and reduces disposal treatment. In this regard, to assure efficient water utilization by finding alternative water sources, sewage sludge collected from the wastewater treatment plant (WWTP) was recently investigated because it could represent a suitable resource for producing biomethane within the context of a circular economy. Therefore, this study aims at improving the current knowledge on the feasibility of biomethane production from sewage sludge by optimizing the logistic-supplying phase. In this regard, a GIS-based model was developed and applied to the Emilia-Romagna region to consider the existing networks of WWTPs and biogas systems to valorize sewage sludge for bioenergy production and minimizing environmental impact. The results of the GIS analyses allowed to localize the highest productive territorial areas and highlighted where sewage sludges are abundantly located and could be better exploited within agricultural biogas plants. Finally, the achieved results could help plan suitable policy interventions that are centered on biomass supply and outputs diversification, governance, and social participation, since the regulatory framework could play a crucial role in planning the reuse of these wastes for developing a more sustainable biomethane sector in line with the green economy goals.

Keywords: sewage sludge; biogas; biomethane; GIS; spatial analysis; waste valorization; renewable energy; circular economy

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1. Introduction

The world population is estimated to reach 9.8 billion by 2050 and around 11.2 billion by 2100 [1]. With this increasing population, a significant amount of fuel may be in demand to aid the energy requirements in the coming years [2]. The renewable energy sources for producing electricity and heat could reduce the negative impact of fossil fuels on GHG released into the atmosphere [3–5] by playing a key role in the current CO2 mitigation policies. Among the suitable renewable energy sources that the past few decades have been developed, biomasses are one of the most important renewable energy sources [6]. Furthermore, due to the depletion of natural resources, the current society needs to re-evaluate these resources sustainably [7]. Among these, water is a fundamental resource for sustaining life. Water sustainability is among the most discussed sustainability issues in the last years in which every applicable sustainability principle has been adopted for water from reuse to recycle [8,9]. In this regard, through the concept of the circular economy, which aims for recovery/reuse strategies, new innovative technologies/processes for efficient water utilization, finding alternative water sources (i.e., mainly treated urban wastewater), and closing the water-related loops to balance water demand and supply have been triggered [10].

Furthermore, nutrients, organic matter, cellulose, and biopolymers could also be recovered from wastewater treatment processes (considering both liquid effluents and sludges) to create durable biocomposites [11] and finally, energy. In fact, as the global demand for renewable energy and organic matter increases, organic wastes, including sewage sludge, could be one of the available resources for this purpose [12].

Sewage sludge (SS) as main byproduct of wastewater treatment plants (WWTPs) could be used as substrate or soil fertilization and remediation and, also as energy resource for producing electricity and heat trought conventional technologies. Due to the increase in population and rapid industrialization, there has been a growth in WWTPs. As a result, the amount of SS produced from the WWTPs increased drastically in recent decades, thereby causing a detrimental effect on the environment. Therefore, due to its huge quantity and high treatment costs, the development of effective sludge disposal strategies has attracted increasing attention [13–15]. Sludge utilization is also an important pathway to decrease negative environmental impacts, which might upgrade the conventional WWTPs into innovative producers of clean water, energy, and resources [16]. With the increase in the production of SS and its potential to contaminate the environment, sustainable solutions for sludge disposal must be urgently developed.

Waste sorting policies that reduce municipal solid waste generation and increase resource recycling efficiency are becoming more popular. It is well-known that in WWTPs, SS is produced on a large-scale as a byproduct [17] that contains a large amount of organic matter and other pollutants and needs proper treatment, management and disposal to fulfill the concept of reducing, reusing and recycling [18,19]. Furthermore, since SS handling and disposal account for up to 50% of the total wastewater treatment costs [20–22], its reuse is economically viable and environmentally sustainable compared to waste handling and landfilling [23,24]. In this regard, anaerobic digestion (AD) technology is considered an environmentally friendly and cost-effective technology that is becoming a more desirable option for sustainable management of these biodegradable wastes with high moisture due to fuel energy recovery and low carbon footprint [25]. In detail, AD technology has a high potential for significant reduction of waste through generating high-value products [26], biogas, which can be used for electrical and thermal energy production, transport or as the substitute for natural gas (biomethane) and digestate, which is suitable as a fertilizer for agricultural production, due to high ammonium N/total N ratio [27]. Those advantages have been recognized by the European Commission, which has regarded in EU waste legislation [28] AD as a recycling operation in the waste hierarchy [29].

To date, extensive works have been undertaken in evaluating substrate types, operating parameters and pretreatment methods on the process performance of AD process [25,30–33]. Recent successes in full-scale AcoD implementation demonstrate the potential role of WWTPs as energy producers [34]. The advantages of SS-AD are widely recognized. In many countries, the technology is well developed [35]. A large volume of the biogas generated in AD plants today throughout the globe comes from plants developed over local wastewater treatment systems, where huge opportunities lie to be utilized for energy generation [36]. Several WWTPs have become net energy producers [37–39] (i.e., the Grevesmuhlen WWTP in Germany converts a mixture of primary sludge, waste activated sludge, and grease to biogas; the Köhlbrandhöft plant in Germany also produces 15% more electricity than it consumes on an annual basis) [40].

A water supply and treatment system should ensure the sustainability of the technology considering the water–energy–food–ecosystem (WEFE) nexus in urban and rural planning [41]. In this regard, while implementing these technologies in terms of the governance of environmental resources, territorial and land boundaries represent a big issue. To define the perspective of shifting to renewable energy systems, the first step is to estimate assessing the biomass technical potential, since different biomasses have different yields, yearly schedules, and characteristics and, accordingly, have distinct economic values, which influence, for example, the economic feasibility of the required transportation distances. Thereby, one crucial step for establishing bioenergy plants is finding viable locations for them. Methods based on geographical information systems (GISs) have been used in many disciplines as decision-making tools because they can solve location-allocation-related problems through, for example, minimizing transportation distances [42,43].

Feasible biomass transportation distance depends on feedstock type, and it is affected by several factors. In this regard, GIS provides several tools for solving optimal logistic solutions and minimizing biomass transportation costs [44]. The present study aimed to develop a GIS-based tool for assessing the potential exploitation of SS-AD systems. In particular, the study was focused on the valorization of SS in AD plants not specifically built for this purpose, mixed with other feedstocks (e.g., AD plants for agricultural and agro-industrial wastes, animal manure, etc.). The developed model can help local stakeholders to optimize bioenergy plant location/feeding. The methodology was assessed in the Emilia-Romagna region, as it is the region with the most developed biogas (AD) network in Italy. In this regard, the applied GIS-based method can find the highest potential territorial areas to reuse SS for bioenergy production based on a spatial analysis by combining the locations where SS are produced and those where SS could be exploited for energy purposes.

2. Materials and Methods

2.1. Study Area

The Emilia-Romagna, one of the 20 regions of Italy, is located in Northern Italy, mainly within the Padana plain, covering approximately 22,000 km^2, with a 130 km coastline along the Adriatic Sea.

Emilia-Romagna is one of the wealthiest and most developed regions in Europe, with the third-highest GDP per capita in Italy.

A total of 48% of the region consists of plains, while 27% is hilly and 25% mountainous. The northern border of the Emilia-Romagna follows the river's path for 263 km (163.42 mi). The Po River is the largest Italian river and borders Emilia-Romagna's northern side, after crossing many regions, and has an average annual flow of about 1500 m^3/s. It is the main surface water source for irrigation in the region.

Emilia-Romagna has been, over the years, a highly-populated area, and currently, its population is about 4.4 million, as shown in Table 1. Until the end of 2010s very high increase both of urban-industrial areas and of seminatural areas due to the abandonment of agricultural lands was recorded. Nowadays, Emilia-Romagna is considered one of the richest regions of Europe. Since it is considered Italy's biggest agricultural area, agriculture contributes to the regional economy and contributes to achieving important results.

Despite the depth and variety of industrial activities in the region, agriculture has not been eclipsed.

Emilia-Romagna hosts part of the largest plain in Italy (Padana Plain or Pò Valley) and, therefore, quite a well-functioning regional agriculture that makes this region among the leading regions in the country, with farming contributing 5.8% of the gross regional product. The agricultural sector has aimed for increased competitiveness using structural reorganization and high-quality products. This has led to the success of marketed brands [45].

Regarding the climate pattern, it is warm and temperate, characterized by hot/muggy summer and cold/damp winter [46]. This climate pattern and the large agricultural land area make Emilia-Romagna a region with a great potential for bioenergy production.

In this regard, however, since a feed-in tariff was introduced at the beginning of 2009, the diffusion of biogas production has been causing several unforeseen problems [47–49], e.g., economic difficulties. In any case, overall, Emilia-Romagna is the region with the highest number of AD plants for energy production from agricultural sources and wastes (i.e., energy crops, but also animal manure/wastewater and agro-industrial wastes) [50–52].

Table 1. Distribution of area, population, number of municipal WWTPs and population equivalents (*PE*) in Italy [45].

Region	Area (kmq)	P (n.)	WWTP_2015 (n.)				*PE* (n.)			
			Primary	Secondary	Tertiary	Total	Primary	Secondary	Tertiary	Total
Piedmont	25,387.08	4,424,467	2619	1177	92	3888	341,859	1,306,759	4,554,540	6,203,158
Aosta Valley	3260.90	128,298	274	25	4	303	40,382	161,364	131,540	333,286
Liguria	5416.22	1,583,263	650	100	26	776	442,387	1,337,891	783,894	2,564,172
Lombardy	23,863.45	10,002,615	725	400	373	1498	128,780	1,106,203	10,167,397	11,402,380
Trentino Alto Adige	13,604.92	1,055,934	118	30	87	235	49,796	82,500	2,379,328	2,511,624
Veneto	18,407.27	4,927,596	665	224	259	1148	105,175	625,858	4,729,467	5,460,575
Friuli-Venezia Giulia	7862.27	1,227,122	398	265	82	745	62,658	254,377	1,094,068	1,411,103
Emilia-Romagna	22,452.55	4,450,508	1341	451	245	2037	108,032	691,231	5,069,226	5,868,489
Tuscany	22,986.95	3,752,654	610	493	200	1303	112,033	932,667	5,064,484	6,109,184
Umbria	8464.25	894,762	511	252	46	809	32,656	192,744	885,398	1,110,798
Marche	9401.33	1,550,796	376	310	119	805	34,049	283,074	1,061,342	1,378,465
Lazio	17,232.12	5,892,425	88	405	142	635	132,592	4,175,148	1,914,769	6,222,509
Abruzzo	10,831.68	1,331,574	1043	362	30	1435	145,460	1,122,805	620,768	1,889,033
Molise	4460.51	313,348	66	113	23	202	81,364	163,127	268,739	513,230
Campania	13,670.84	5,861,529	165	219	89	473	327,563	4,009,536	2,333,745	6,670,844
Apulia	19,540.85	4,090,105	5	8	176	189	29,998	351,627	4,406,093	4,787,751
Basilicata	10,073.29	576,619	2	82	88	172	1601	214,545	445,675	661,821
Calabria	15,221.90	1,976,631	188	206	48	442	382,240	1,112,019	765,307	2,259,566
Sicily	25,832.40	5,092,080	118	239	57	414	398,022	3,349,392	957,952	4,705,366
Sardinia	24,100.14	1,663,286	22	243	123	388	72,887	537,546	2,565,122	3,175,555
Total	302,070.92	60,795,612	9984	5604	2309	17,897	3,029,642	22,010,413	50,198,854	75,238,909

In Italy, agriculture accounts for 60% of total water consumption. In the Emilia-Romagna region, water consumption for irrigation is 66%. Agriculture's extremely high share of water consumption affects both surface and underground water resources. In the Po river basin, where 40% of Italy's national GDP is generated, this situation has led to both water body deterioration and an imbalance between surface and underground water ecosystems.

Considering the high amount of WWTPs as shown in Table 1, all these conditions urge the reuse of treated wastewater and sewage sludges for environmental preservation, resource recovery, and bioenergy production.

2.2. Developed GIS-Based Model and Data Analysis

In this study, an extensive database was improved by considering several statistical sources, i.e., ISTAT [51] at the national level, and the minERva database [53] provided by the Emilia-Romagna region, to localize by GIS analyses the highest potential territorial areas to reuse SS for bioenergy.

The ISTAT database was adopted first to acquire data for identifying the number of WWTPs located in the study area during the selected time interval [51]. All recorded data were then elaborated for creating GIS maps.

The base maps adopted for producing thematic maps in the GIS software included the administrative boundaries provided by the metadata catalog of the Italian geoportal.

The MinERva database was used to acquire data about the quantity of SS produced by each located WWTPs. Furthermore, it was used to export data for localizing bioenergy plants available in the study area [53]. All data recorded were elaborated before using them for GIS analyses.

By initially analyzing all the available data, the distribution of WWTPs in Italian regions was obtained by highlighting the regions with the highest concentrations by adopting the Jenks tool available in QGIS software v.3.10.11, a free software provided by Open Source Geospatial Foundation (Chicago, USA). The Jenks natural break tool available in QGIS software was applied for classifying the Italian regions based on the number of WWTPs by emphasizing their differences.

Then, a deep analysis on data related to WWTPs located in the Emilia-Romagna region was performed. Combining data obtained from GIS elaborations and from Istat and minERva databases, a suitable index for selecting the territorial area (i.e., province) within the Emilia-Romagna region was computed. The index based on the population equivalent (PE_{index}) was calculated for each province within the Emilia-Romagna region by adopting the following equation (Equation (1)):

$$PE_{index} = \frac{PE_{average}}{PE}\% \quad (1)$$

where PE is the total amount of population equivalent within each considered province, and $PE_{average}$ is the average of PE by considering all the WWTPs located in the considered province.

The index was applied in GIS, and by adopting the Jenks natural break tool, the classification of the provinces was obtained to select that province as a suitable study area.

Based on the selected study area, data recorded from the minERva database were elaborated and reported on a GIS map to classify the territorial areas based on SS amount, by maximizing the class difference.

The next step of the developed methodology involved analyzing bioenergy plants by elaborating data recorded from the minERva database. All data were used to produce GIS maps by grouping bioenergy plants by biomass and then by biogas. Then by adopting the Jenks natural break tool, the territorial areas were analyzed, and the overlay of data contribute to obtaining those areas with the highest concentration of plants, both bioenergy plants and WWTPs.

The last step focused on assessing the potential territorial areas to reuse SS for bioenergy production based on a spatial analysis combining the locations where SS are produced and those where SS could be exploited for energy purposes. With this aim, a suitable index (SS_{index}) at municipal level, which describes the classification of most suitable areas for sustainable reusing SS as biomass for anaerobic digestion by optimizing the supply logistic phase was developed by taking into account both the amount of SS and the biogas plants nowadays available in the study areas. SS_{index} was computed by the following equation (Equation (2)):

$$SS_{index} = \frac{SS_{municipality}}{SS_{province}}\% + \frac{BP_{municipality}}{BP_{province}}\% \quad (2)$$

where $SS_{municipality}$ is the total amount of SS produced by each considered municipality, $SS_{province}$ is the total amount of SS produced within the province, $BP_{municipality}$ is the total number of biogas plants located within each considered municipality, and $BP_{province}$ is the number of the total biogas QGIS software to classify the municipalities of the study area. By adopting the Jenks natural break tool, the suitable territorial areas with the highest potential for reusing SS for bioenergy production and, therefore, where planning new locations for in a circular and green economy perspective by minimizing distances were selected.

3. Results and Discussion

Data extracted from the Istat database were elaborated and shown in Table 1. By analyzing Table 1 Emilia-Romagna region with about 2037 WWTPs plants represents 11% of the total WWTPs plants located in Italy, following the Piemonte region that represents 22% of the total Italian WWTPs (i.e., about 3800 WWTPs).

From Figure 1, it is also possible to see the WWTPs Italian distribution by confirming the highest concentration in the region of Piedmont, Emilia-Romagna, and Lombardy that represent more than 40% of the Italian WWTPs. In detail, as reported by the Istat database related to the 2015 year, 2037 WWTPs are located in the Emilia-Romagna region, and among these, 66% is represented by the primary sector, 22% by secondary sector, and 12% by tertiary one.

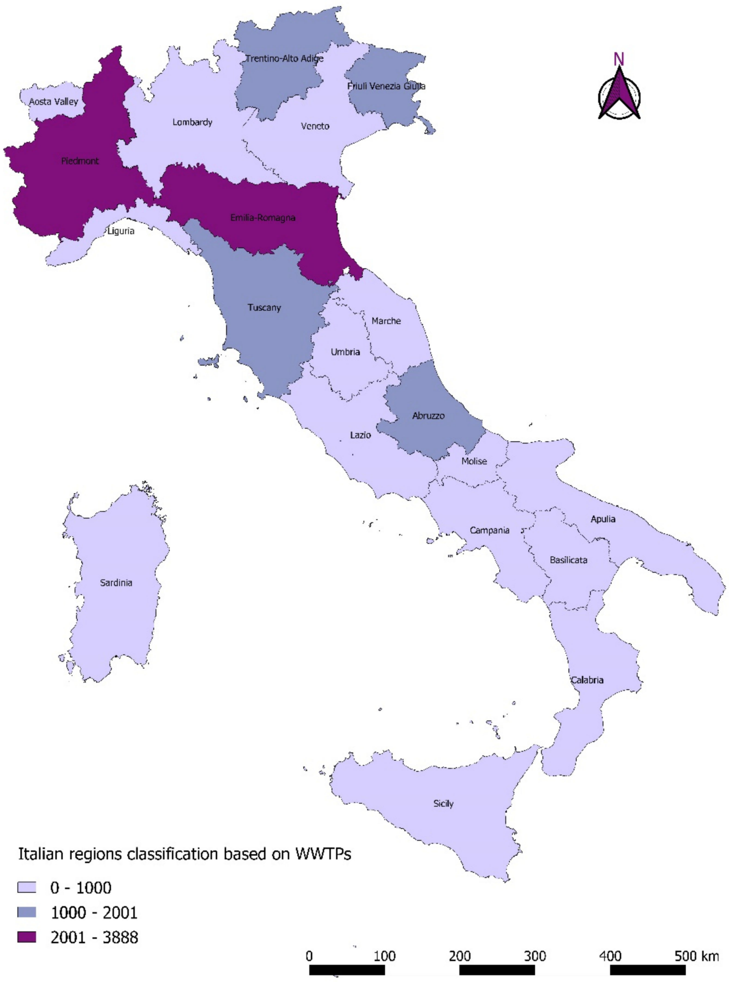


Figure 1. WWTP distribution at the territorial level within the Italian regions.

By deeply analyzing WWTPs data for each region, among those, the Emilia-Romagna region in the last years implemented its wastewater reuse systems by increasing the number of WWTPs and by activating programmed utilization for irrigation and environmental purposes accordingly to European Strategies.

As shown in Table 2, the available data on WWTPs of the Emilia-Romagna region were elaborated by selecting only those plants with secondary (ST) or tertiary treatment (TT) levels, i.e., excluding the plants where only pretreatments and primary settlement occur.

Table 2. WWTPs in operation in the Emilia-Romagna region as a function of treatment level. ST = secondary treatment; TT = tertiary treatment.

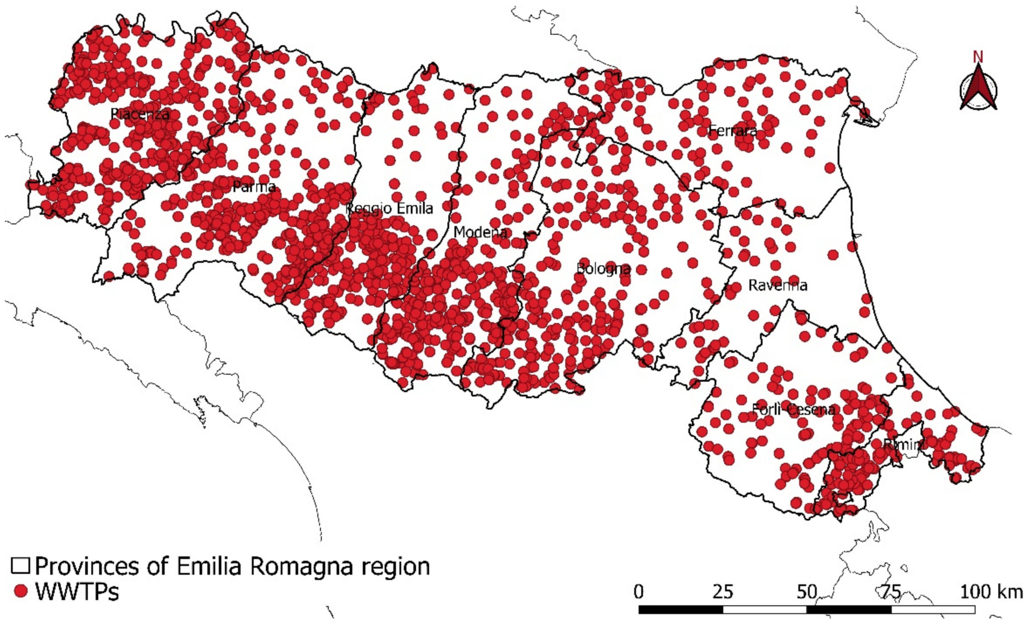
Provinces	WWTPs			*PE*
	ST	TT	Total	
Piacenza	87	14	101	393,077
Parma	85	42	127	797,930
Modena	47	33	80	1,217,634
Bologna	110	34	144	1,449,060
Reggio Emilia	61	19	80	762,985
Forlì-Cesena	39	9	46	788,026
Rimini	25	5	30	928,761
Ferrara	74	20	94	719,823
Ravenna	16	15	31	1,188,098
Total	544	191	733	8,245,394

ST: secondary treatment; TT: tertiary treatment; *PE*: population equivalent.

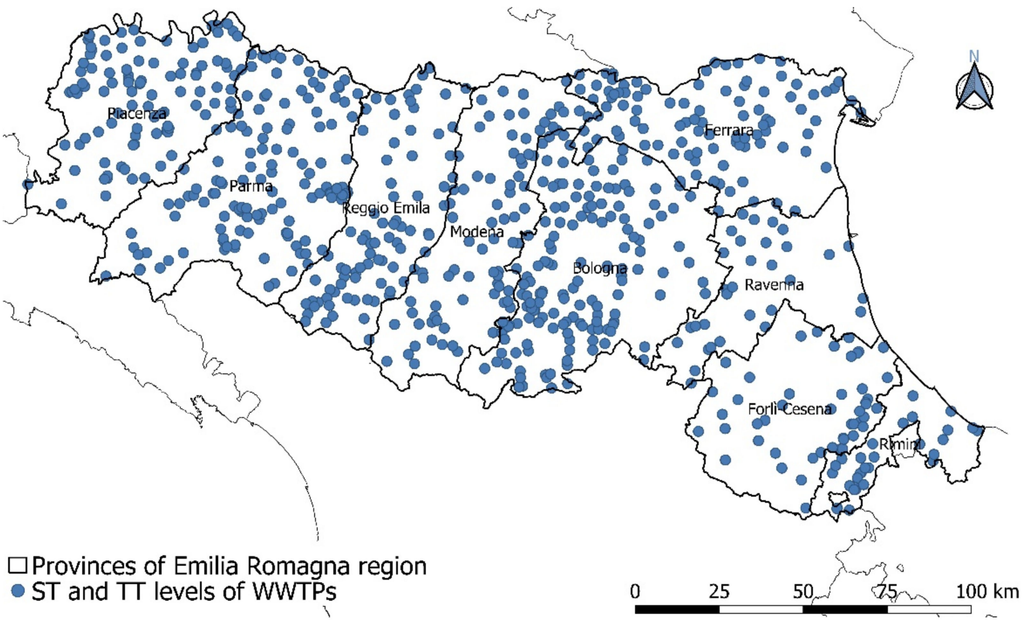
733 WWTPs considering both ST (74% of the total WWTPs) and TT (26% of the total) are actually in operation in the Emilia-Romagna region by serving a total population of about 8 million inhabitants. Several treatment plants were built to improve water quality and to allow extensive water reuse.

By using the QGIS tool, first, all the WWTPs were located on the GIS map (Figure 2a). Then, by adopting the geoprocessing tool available in QGIS software, only the WWTPs related to ST and TT are considered and shown in Figure 2b.

Then, as shown in Table 3, data were elaborated to compute, using Equation (1), the PE_{index}, which aims to classify the Emilia-Romagna provinces by taking into account the total amount of served PE and the average of served PE, respectively, for each province within the region.



(**a**)



(**b**)

Figure 2. WWTP distribution at the territorial level within the Emilia-Romagna region: (**a**) WWTP localization considering all treatment levels; (**b**) WWTP localization considering only ST and TT levels.

Table 3. Computation of the PE_{index} value for the provinces of the Emilia-Romagna region.

Provinces	WWTPs	*PE*	Average *PE*	PE_{index}
Piacenza	101	393,077	3892	0.990
Parma	127	797,930	6283	0.787
Modena	80	1,217,634	15,220	1.250
Bologna	144	1,449,060	10,063	0.694
Reggio Emilia	80	762,985	9537	1.250
Forlì-Cesena	46	788,026	17,131	2.174
Rimini	30	928,761	30,959	3.333
Ferrara	94	719,823	7658	1.064
Ravenna	31	1,188,098	38,326	3.226
Total	733	8,245,394	-	-
Average	81	916,155	15,452	1.641

PE: population equivalent; PE_{index}: computed index.

By considering the computed PE_{index} average, only the provinces with an PE_{index} greater than the average value of the PE_{index} were selected, as shown in Figure 3.

As shown, the selected provinces (Rimini, Ravenna and Forlì-Cesena) are mainly located in the coastal areas. Among these three selected provinces, Forlì-Cesena was selected as the focus study area because it has the highest number of WWTPs (Table 3). In this regard, the highest number of WWTPs, during the logistic-supplying phase could be one of the crucial factors for reusing the produced SS for renewable energy production (i.e., biogas or biomethane). As shown in Figure 4, all WWTPs (ST and TT levels) were located within the Forlì-Cesena province (Figure 4a). The municipalities of Sogliano al Rubicone, Cesena, and Roncofreddo with the highest concentration are highlighted (Figure 4b). The Jenks natural break tool available in QGIS software was applied for classifying the municipalities by emphasizing their differences.

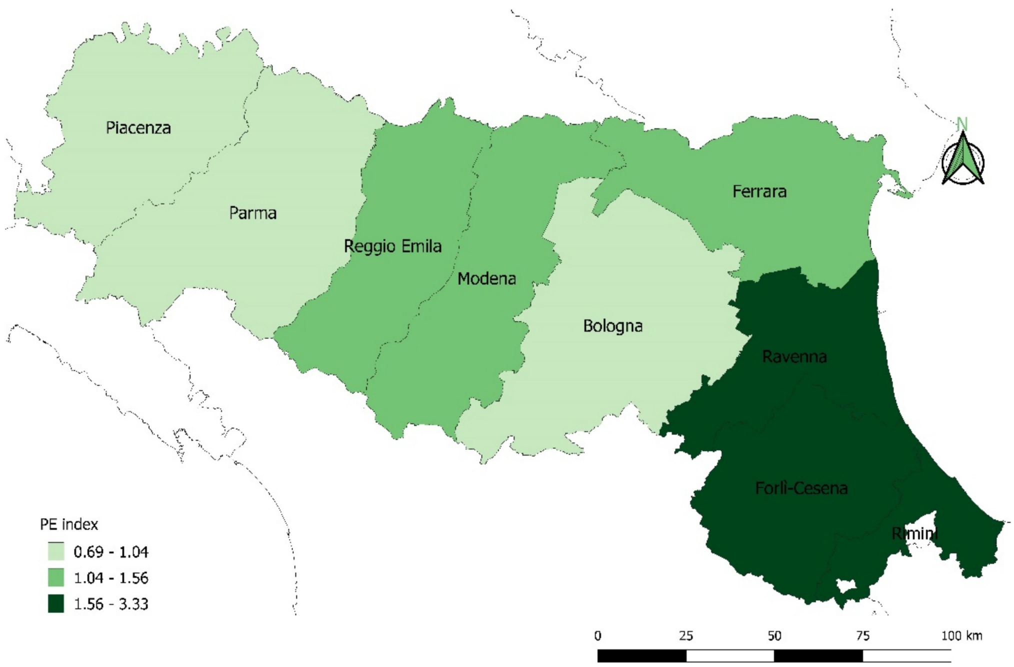
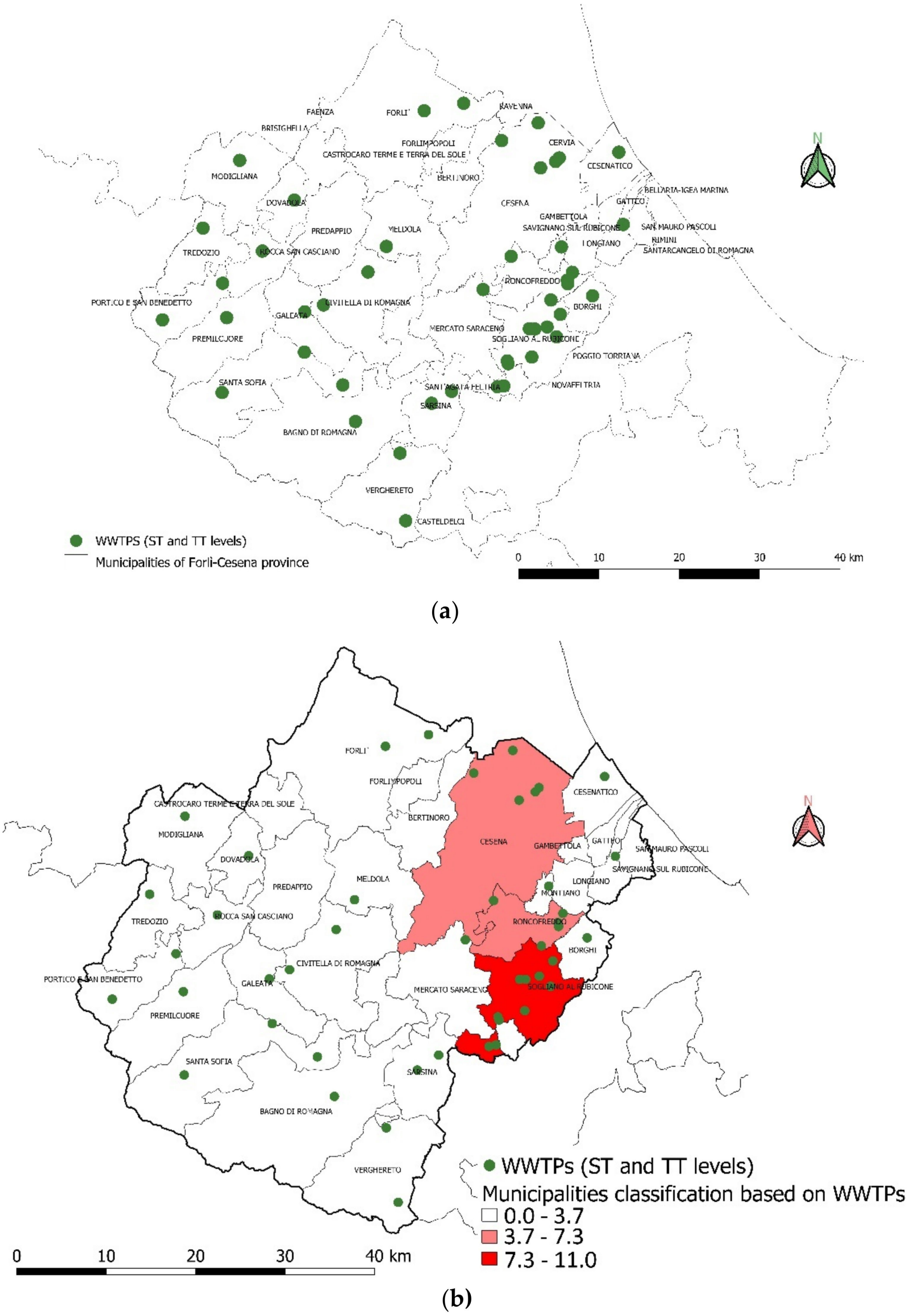


Figure 3. PE_{index} distribution at the territorial level within the Emilia-Romagna region.

For each WWTP, data related to the processed SS were recorded and elaborated. Then, as shown in Figure 5, the municipalities of Forlì-Cesena province were grouped based on the estimated SS as potential biomass for producing renewable energy (i.e., biogas or biomethane) applying the Jenks break tool. The municipalities of Cesena, Forlì, and Savignano sul Rubicone were identified as the most promising.



(**a**)

(**b**)

Figure 4. WWTP distribution at the territorial level within the province of Forlì-Cesena: (**a**)WWTPs distribution; (**b**) Municipalities classification based on WWTPs distribution.

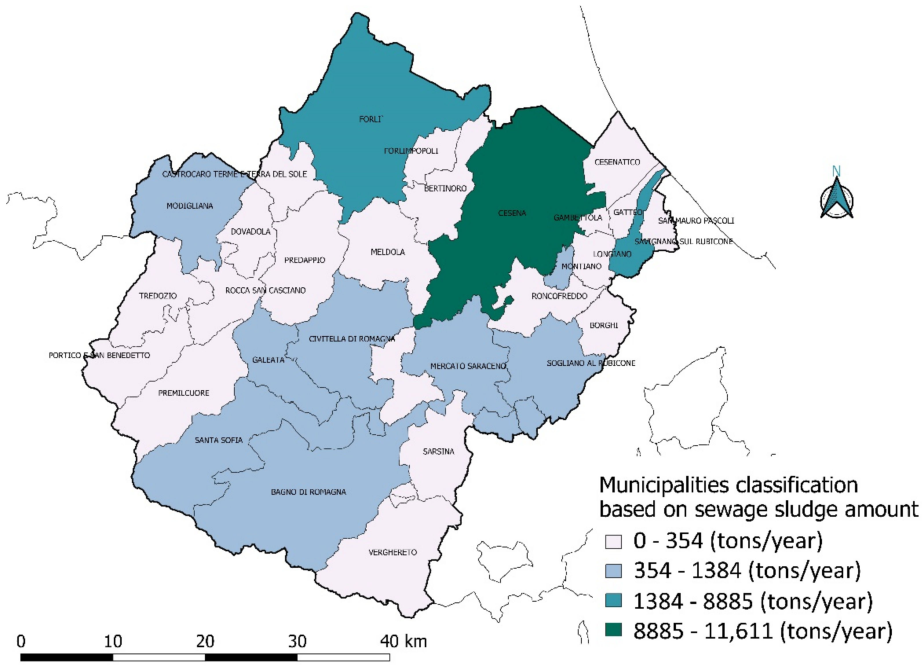


Figure 5. Forlì-Cesena's municipalities classification based on the amount of processed sewage sludge at the territorial level.

By comparing results obtained and shown in Figures 4 and 5, the municipality of Cesena had the highest concentration of WWTPs and the highest amount of SS.

The next step was the localization at the territorial level of the bioenergy plants already active in the province of Forlì-Cesena (Figure 6). Among the thirteen located bioenergy plants, nine of them are dedicated to producing biogas, the other ones (i.e., four) are dedicated to producing energy from biomass (i.e., energy from vegetable oil). Furthermore, by elaborating data obtained from the MinERva dataset [53], among the nine located biogas plants, seven plants are agricultural biogas plants fed by agri-food and agricultural waste, the other two plants contribute to producing biogas by anaerobic co-digestion of municipal solid wastes. These two biogas plants are located within the municipalities of Cesena and Sogliano al Rubicone.

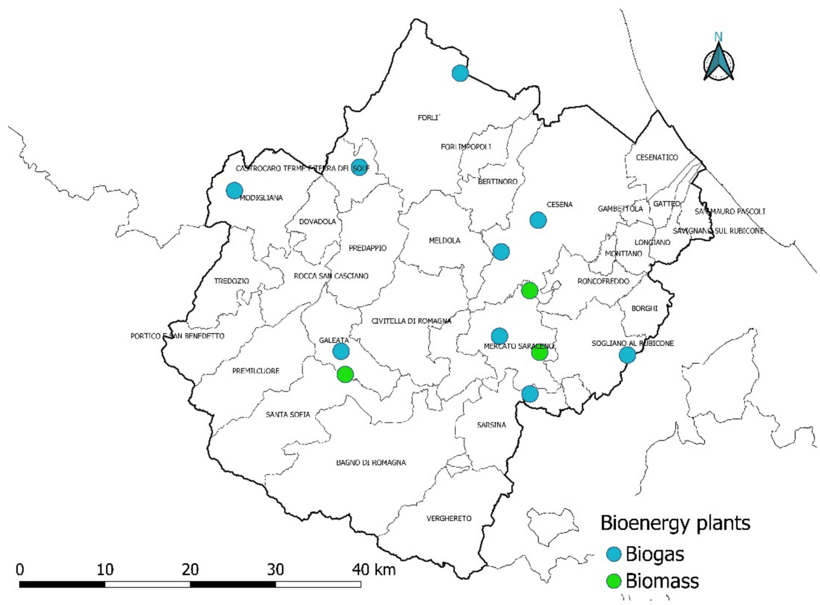


Figure 6. Forlì-Cesena's municipalities classification based on the amount of processed sewage sludge at the territorial level.

After their localization, data were elaborated to obtain a GIS map for allowing selecting the municipalities with the highest number of existing plants (Figure 7).

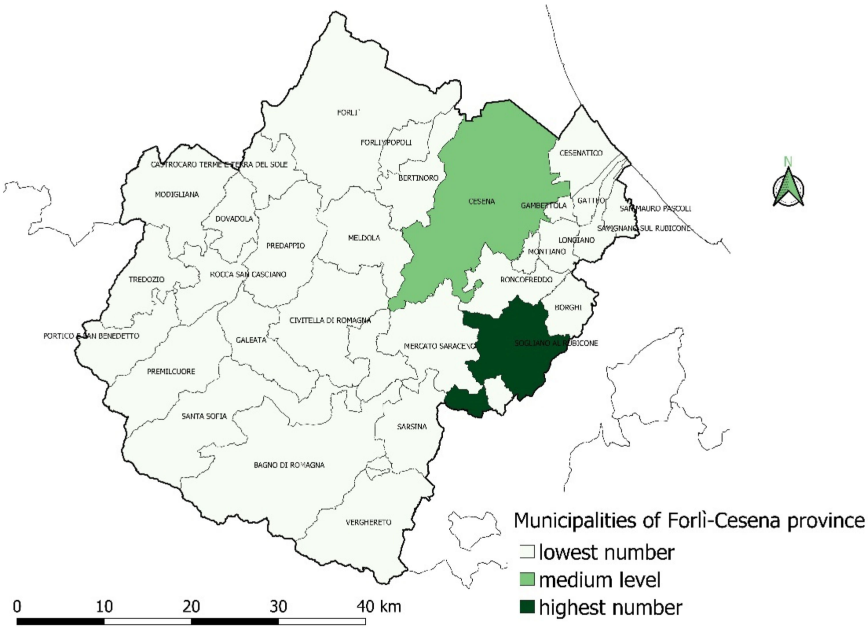


Figure 7. Forlì-Cesena's municipalities classification based on the number of plants that produce (WWTPs) and can potentially use (biogas plants) sewage sludge.

The classification shown in Figure 7 allowed selecting the municipalities of Cesena and Sogliano al Rubicone.

The last step of the research was developing a suitable index to classify the municipalities to find those which represent the most suitable areas for sustainable reusing SS as biomass for anaerobic digestion by optimizing the supply logistic phase.

Therefore, by adopting Equation (2), the index was computed and reported in QGIS software. Then, a GIS map was obtained by adopting the Jenks natural break tool, as shown in Figure 8.

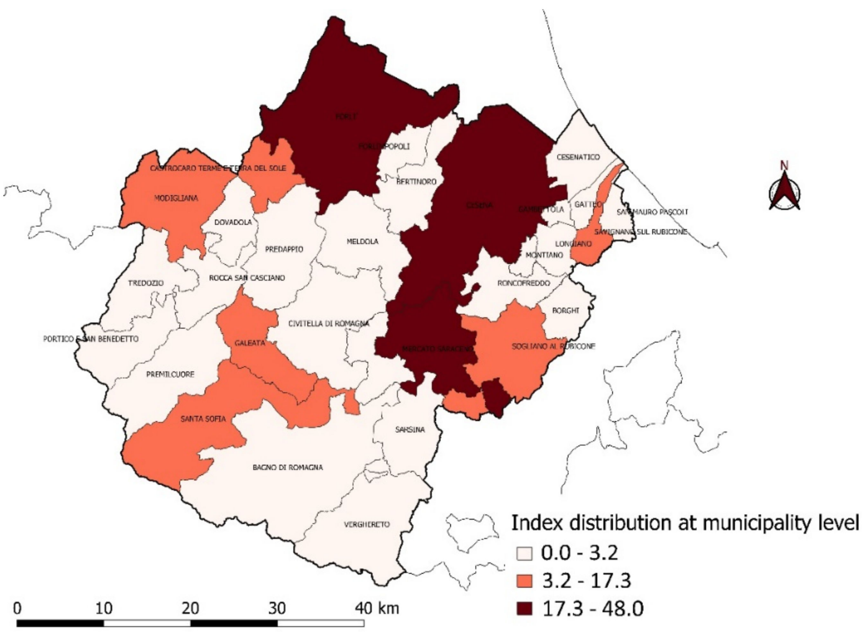


Figure 8. Index distribution at the territorial level within the municipalities of Forlì-Cesena province.

Figure 8 shows the main results of the research. By starting from the municipalities of Cesena, Forlì, and Mercato Saraceno, it could be possible to reuse SS for producing renewable energy by taking into account transport distances between WWTPs and biogas plants already installed within the selected study area.

Today, these findings are crucial for minimizing environmental impacts derived from the logistic-supplying phase, so it is important to plan the suitable locations for new plants (both considered types) in a circular and green economy perspective.

Some research studies were carried out by combining GIS tool and statistical database, by taking into account different sources of biomass, but with the same objective of reducing environmental impacts related to logistic supply phase, with the key criterion of minimizing transportation cost [5,7,42,43]. In line with the results reported here, all of these studies demonstrated that new bioenergy plants must be located as near as possible to the biomasses production sites.

4. Conclusions

The study, developed by taking into account both collected data and GIS-based analyses, allowed elaborating and mapping: (i) the spatial localization of the WWTPs and of the bioenergy plants, and (ii) the quantification of SS produced within the study area. Furthermore, a specific index (SS_{index}) was developed and calculated at the territorial level under a GIS model, aimed at finding the highest potential territorial areas to reuse in a sustainable way the produced SS for bioenergy production by taking into account the biogas network of the Emilia-Romagna region. The developed GIS model represents a simple tool to easily identify the potential synergies between the existing regional/local networks of i) WWTPs, where SS is produced with some environmental disposal problems, and of ii) agricultural AD (biogas) plants, where SS could be valorized, mixed with other agricultural feedstocks. Based on GIS spatial analyses, the model can provide information that could help optimize the supply chain of biogas systems already in operation. However, it could also be a useful tool for local stakeholders and policymakers to plan new bioenergy plants, identify suitable areas for finding optimal logistic solutions, and minimize SS transportation costs, which is a relevant condition to reduce their transport costs.

Hence, it could be helpful for reducing the significant environmental impact of the SS produced by WWTPs and increase bioenergy production within the context of water–energy nexus, due to the fact that through anaerobic co-digesting SS and organic waste, nowadays several WWTPs worldwide have achieved energy self-sufficiency and produced surplus biogas.

Some limitations must still be overcome through further research developments to fully implement SS reuse in AD plants. Specifically, (i) the effects of SS on bioenergy production in AD systems using other feedstocks should be better investigated, case-by-case, to find the optimal diet for co-digestion; (ii) the AD plant operators should be allowed to use SS mixed with other biomasses as feedstock for co-digestion. According to current Italian legislation, this could be often controversial and subjected to regulatory constraints since SS is considered waste, and a specific authorization may be needed.

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