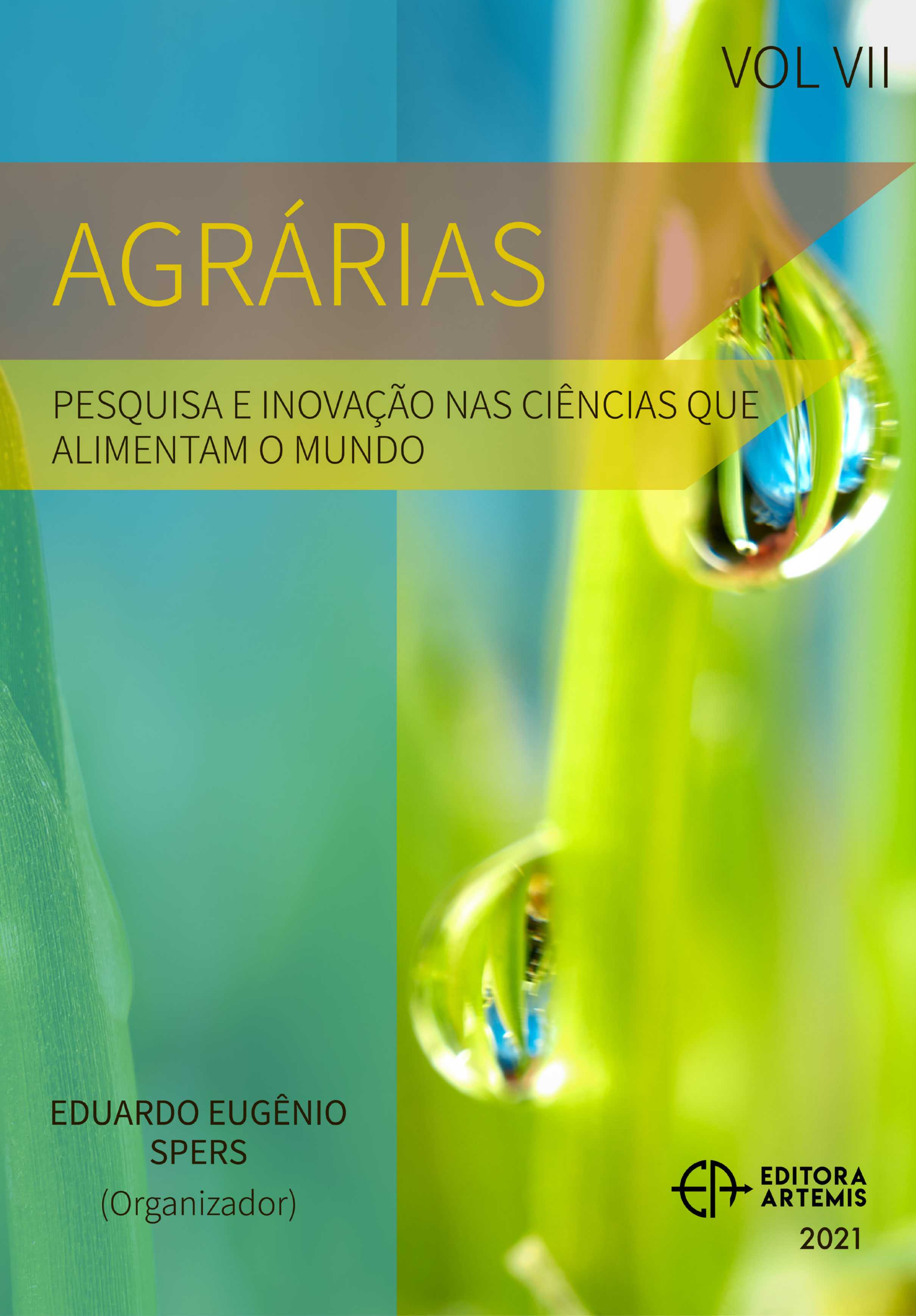

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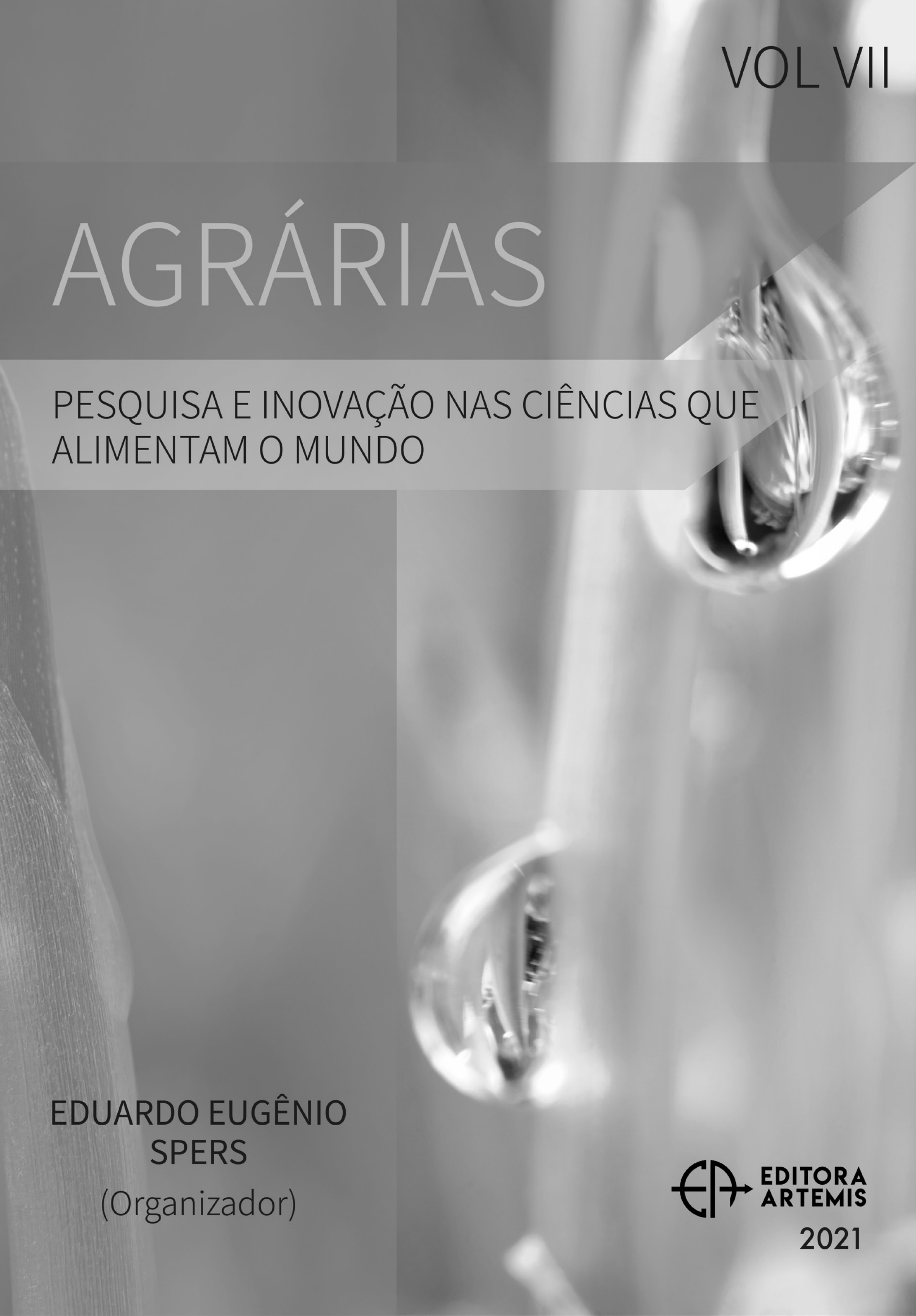

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APRESENTAÇÃO

As Ciências Agrárias são um campo de estudo multidisciplinar por excelência, e um dos mais profícuos em termos de pesquisas e aprimoramento técnico. A demanda mundial por alimentos e a crescente degradação ambiental impulsionam a busca constante por soluções sustentáveis de produção e por medidas visando à preservação e recuperação dos recursos naturais.

A obra **Agrárias: Pesquisa e Inovação nas Ciências que Alimentam o Mundo** compila pesquisas atuais e extremamente relevantes, apresentadas em linguagem científica de fácil entendimento. Na coletânea, o leitor encontrará textos que tratam dos sistemas produtivos em seus diversos aspectos, além de estudos que exploram diferentes perspectivas ou abordagens sobre a planta, o meio ambiente, o animal, o homem, o social e sobre a gestão.

Este Volume VII traz 29 artigos de estudiosos de diversos países: são 20 trabalhos de autores da Argentina, Colômbia, Cuba, Equador, Espanha, Japão, México e Portugal e nove trabalhos de pesquisadores brasileiros, divididos em quatro eixos temáticos.

Os doze títulos que compõem o eixo temático **Sistemas de Produção Sustentável e Agroecologia** apresentam estudos sobre diferentes formas de se diminuir, reverter ou harmonizar as consequências da atividade humana sobre o meio ambiente ou desenvolvem temas relativos à importância do solo e da água para a manutenção dos ecossistemas.

Nove trabalhos versam sobre **Sistemas de Produção Vegetal** e os últimos oito capítulos tratam de temas variados dentro do eixo temático **Sistemas de Produção Animal e Veterinária**.

Desejo a todos uma proveitosa leitura!

Eduardo Eugênio Spers

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CAPÍTULO 5

SPATIALLY EXPLICIT MODEL FOR ANAEROBIC CO-DIGESTION FACILITIES LOCATION AND PRE-DIMENSIONING IN NORTHWEST PORTUGAL[1]

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ABSTRACT: The high volumes of animal manure and sewage sludge, as a consequence of the development of intensive and specialized cattle dairy farms in peri-urban areas, pose challenges to local environmental quality and demands for systems innovation. Besides these negative impacts, energy recovery from biogas produced in anaerobic co-digestion processes should contribute to local sustainable development. This research considers technical data obtained from the optimization of biomethanization processes using sewage sludge and cattle manure liquid fraction, aiming

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[1] The content of this chapter contributed to the published paper https://doi.org/10.3390/app11041841

to develop a spatially explicit model including multicriteria evaluation and an analytical hierarchy process to locate biogas production facilities, allocate energy resources and consider biogas unit pre-dimensioning analysis. According to the biophysical conditions and socioeconomic dynamics of the study area (Vila do Conde, Northwest Portugal), a spatially explicit model using multicriteria and multiobjective techniques allowed the definition of suitable locations, as well as the allocation of resources and support pre-dimensioning of biogas facilities. A p-median model allowed us to allocate resources and pre-dimensioning biogas facilities according to distance and accessibility elements. The results indicate: (i) the location of areas with adequate environmental conditions and socioeconomic suitability advantages to install biogas production facilities, and (ii) the ability to compare the options of centralized or distributed location alternatives and associated pre-dimensioning.

KEYWORDS: Geographic information science. Location-allocation. Anaerobic co-digestion. Analytic hierarchy process. Biogas.

MODELO ESPACIALMENTE EXPLÍCITO PARA LOCALIZAÇÃO E PRÉ-DIMENSIONAMENTO DE INSTALAÇÕES DE CO-DIGESTÃO ANAERÓBIA NO NOROESTE DE PORTUGAL

RESUMO: O elevado volume de resíduos de origem animal e lamas domésticas/urbanas, como consequência do desenvolvimento de fazendas de pecuária leiteira intensiva e especializadas em áreas periurbanas, representam desafios para a qualidade ambiental local e demandam por uma inovação de sistemas. Além desses impactos negativos, a recuperação energética do biogás produzido a partir de processos de co-digestão anaeróbia deve contribuir para o desenvolvimento sustentável local. Esta pesquisa considera dados técnicos obtidos a partir da otimização de processos de biometanização utilizando lamas domésticas/urbanas e fração líquida do chorume bovino, visando desenvolver um modelo espacialmente explícito incluindo avaliação multicritério e processo de hierarquia analítica para localizar instalações de produção de biogás e alocar recursos energéticos considerando uma análise de pré-dimensionamento de unidades de produção de biogás. De acordo com as condições biofísicas e as dinâmicas socioeconómicas da área de estudo (Vila do Conde, Noroeste de Portugal), um modelo espacialmente explícito utilizando técnicas multicritério e multiobjetivo permitiu a definição de localizações adequadas, bem como a alocação de recursos e apoio no pré-dimensionamento de instalações de produção de biogás. Um modelo de p-mediana permitiu alocar os recursos e pré-dimensionar as unidades de biogás de acordo com a distância e elementos de acessibilidade. Os resultados indicam: (i) a localização de áreas com condições ambientais adequadas e vantagens socioeconômicas para a instalação de unidades de produção de biogás, e (ii) a capacidade do modelo de comparar as opções de alternativas de localização centralizada e/ou distribuída e o pré-dimensionamento associado.

PALAVRAS-CHAVE: Ciência da informação geográfica. Localização-alocação. Codigestão anaeróbia. Processo de análise hierárquica. Biogás.

1 INTRODUCTION

Economic competitive advantages found in (peri)urban areas promote population concentration, increasing rural-urban interfaces [Winarso *et al.*, 2015] and fostering changes in local consumption patterns and in waste and wastewater spatio-temporal production [Lefebvre *et al.,* 2012]. These processes contribute to sewage sludge (SwS) and animal manure production and accumulation [Lima *et al*., 2015] originating from local rural and urban activities, causing potential pressures and impacts on quality of life and natural resource management [Paolini *et al*., 2018] of these complex socio-ecological systems [Kelly *et al*., 2015]. However, these local or regional problems concerning the excess of organic loads can turn into opportunities resulting from bioenergy and nutrient recovery processes into fertilizers and energy, simultaneously promoting waste reduction and reuse and local circular (bio)economy innovation [Rammel *et al.* 2007].

The prospect of resource scarcity has been a constant challenge, which reaffirms the necessity to develop new approaches and technologies, improve processes and innovate organizational systems. A holistic and transversal approach should incorporate the complex interdependence between water, energy and food resources (water-energy-food nexus) [Biggs *et al*., 2015], integrating the complexity of local socio-ecological systems [Young *et al*., 2006; Torres-Lima *et al*., 2019]. Public wastewater sanitation infrastructures, as major energy consumers within municipalities [Racoviceanu *et al*., 2007], need to adopt strategies that enhance the eco-efficiency of their facilities and that also seek to support other realities within the territory, such as waste and wastewater generating activities, that still lack proper treatment. In this context, dairy intensive farms, as large waste producers, still need the implementation of treatment technologies that promote the energetic valorization of this substrate typology. This reality demands for a local integrated management and spatio-environmental planning of peri-urban areas [Steinhäußer *et al*., 2015; Scarlat *et al*., 2019]. In that regard, the location, dimensioning and operation of some wastewater treatment plants (WWTPs) may be optimized with the integration of both waste and wastewater in order to meet the project dimensioning parameters.

In this context, in a systemic approach to the energy efficiency of the territory, advanced studies have been carried out, aiming at the development of a spatially explicit model for anaerobic co-digestion facility location and pre-dimensioning, considering the spatial distribution of resource supply.

Thus, data, information and knowledge from experimental assays [Coura *et al*., 2021] are integrated both in the definition of environmental, social and economic criteria at planning scale (location, allocation and pre-dimensioning existing and new potential biogas plants) and in biogas facility operation (organizational and logistic solutions) [Spigolon *et al*., 2018].

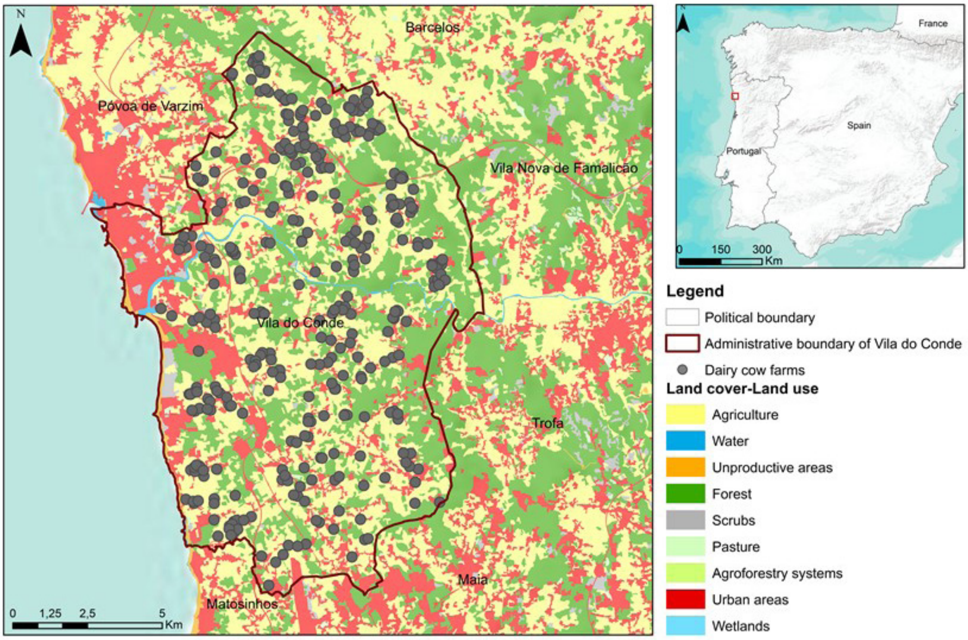
2 MATERIALS AND METHODS

2.1 SCOPE, OBJECTIVES AND RESEARCH FRAMEWORK

The present research aims to develop a spatially explicit model using an analytical hierarchy process (AHP) concerning the suitable location and the pre-dimensioning of biogas units in ACoD systems for sewage sludge and dairy cattle manure liquid fraction (CMLF) (urban and rural) treatment and valorization. The model development considers the test and local reality of Vila do Conde municipality (Northwest; NW Portugal) (Figure 1).

This process assumes that the location and pre-dimensioning of the biogas production units result from the collaboration among decision makers, project promoters, researchers (in environmental and spatial technologies) and technicians involved in land use planning and urban/(agro)industrial waste and wastewater facility development. The analyses and solutions consider: (i) the legal and regulatory framework (European directives, national legislation and national strategies); (ii) local/ sectorial planning and management framework; (iii) experimental data related to AcoD kinetic parameters [Coura *et al.*, 2021]; and other (inter)national reference technical and scientific studies.

Figure 1. Spatial research unit of Vila do Conde municipality (NW Portugal).



2.2 SPATIO-TEMPORAL PATTERNS OF SEWAGE SLUDGE AND DAIRY CATTLE MANURE PRODUCTION AND AVAILABILITY

The analysis and estimation of production, availability and exploitability patterns of waste sludge from WWTPs and cattle manure from urban areas and dairy cattle farms consider: (i) current and future population distribution and economic activity [INE, 2011]; and (ii) local cattle dairy farms' productive structure and the cows' spatial distribution [Alonso *et al.,* 2012].

Waste production pattern definition considers the average values of total solids (TS) production for sewage sludge (16.5kg inhab^{-1} year^{-1}) [GFA, 2000] and for cattle dairy farms (20m^{3} cow^{-1} year^{-1} with 3.5% of dry matter (TS) m^{-3} after solid-liquid manure separation) [CBPA, 997; Brito *et al.,* 2011]. Results obtained from former studies [Coura *et al.*, 2021] are also considered, such as the average ratio between total solids and volatile solids (VS) (65%), the biogas yield (93.3mL gVS^{-1}) and methane yield (48.5mL gVS^{-1}). The models also consider the biogas calorific value of 21.5MJ m^{-3} (electric energy content equivalent of 6kWh m^{-3} and heat energy content equivalent of 2kWh m^{-3}, approximately) [Batzias *et al.,* 2005; Braun, 2007; Rohstoffe, 2008; AQPER, 2019].

2.3 SPATIAL MULTICRITERIA MODEL DEVELOPMENT TO SUPPORT BIOGAS FACILITIES LOCATION

Multicriteria and multiobjective evaluation allows unit location and resource allocation spatial assessment processes by structuring decision problems.

The developed spatial model integrates operations of distance analysis, overlap, interpolation, reclassification, 3D surface analysis and network analysis, and technical and political options regarding the following aspects: (i) social aspects (service level, acceptance, social innovation; (ii) economic dimensions (related to investment, maintenance and operation costs) [Espinosa and Pizarro-Irizar, 2018]; (iii) and environmental conditions (environmental impact and management towards environmental protection). Each criterion and dataset is standardized in spatial reference systems (ETRS89 TM06), and final thematic criteria values were reclassified into categorical scales (0 for exclusion, and a scale from 1, low value, to 5, optimal value).

In this study, the AHP allowed the ranking and weighting of the relative importance of the different factors/criteria in the final results (Ma *et al.,* 2005]. Final values were obtained based on the 9-point classification system described by [Satty, 1991], with consistency coefficients (CC) with values below 0.10 being accepted.

2.4 MULTICRITERIA MODEL VALIDATION, RESOURCES ALLOCATION AND BIOGAS PLANTS PRE-DIMENSIONING

Multiobjective and pre-dimensioning analysis considers alternative scenarios (centralized considering 1 to 3 biogas production facilities or distributed biogas production systems, from 5 to 8 new units) related to the number and biogas plants dimension (considering the amount of sewage sludge and dairy cattle manure available).

Location-allocation analysis and p-median problem [Church and Medrano, 2018] intend to find optimum locations of facilities such that the product of the (weighted) distance and impedance between each demand location and the nearest facility is minimized, as well as allowing test and maximize couverture [ESRI, 2019].

These new polygons allow the use of overlay operations aiming to estimate the allocation of feedstock based on sewage sludge and cattle manure availability and associated biogas plant capacity (m^3biogas $year^{-1}$) to the resulting potential electric and heating energy.

2.5 MULTICRITERIA SPATIALLY EXPLICIT MODEL DEVELOPMENT

Multicriteria model validation, the location selection and the pre-dimensioning (based on resource allocation and bioenergy potential) of biogas production facilities support the results presentation and scientific and technical discussion. A final critical evaluation of the methodological approach and results was carried out, followed by proposal definition in order to transform the research products into thematic and spatial decision support tools at future biogas production facilities' project and management phases.

3 RESULTS

3.1 SEWAGE SLUDGE AND CATTLE MANURE SPATIO-TEMPORAL PATTERNS

The resident population (in Vila do Conde municipality) increased as a result of local and regional improvements in accessibility to the closest Oporto metropolitan area (NW Portugal). The population concentration in coastal, riverside and near highway main accesses, as well as near industrial areas and the services sector, results in a considerable increase in the current and potential distribution dynamics of municipal waste and sewage sludge.

The 368 dairy cattle local farms present distinct physical, economic and social dimensions (between 13 and 620 cows, mean of 67 cows per farm) using semi-intensive production systems with a variety of production technologies. Despite this variability, most farms are small (under 50 cows per farm).

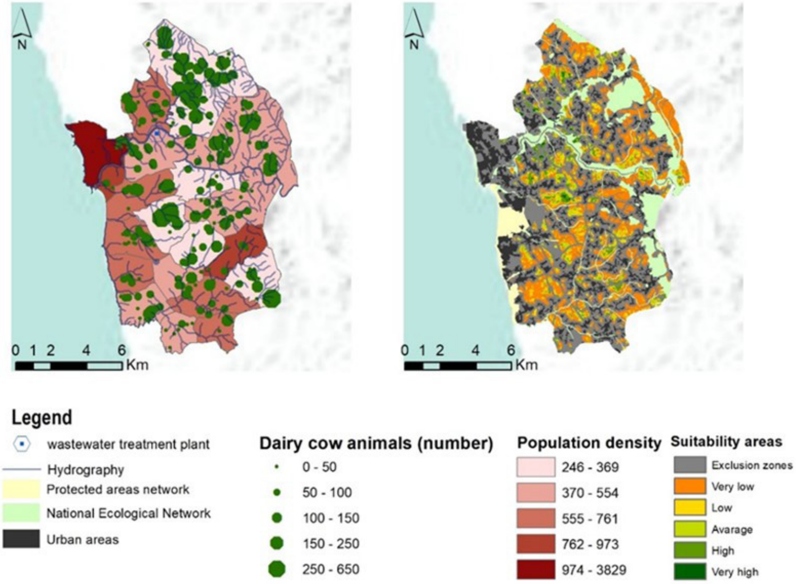
The results indicate that sewage sludge and dairy cattle manure production present different spatial and temporal patterns. Municipal wastewater is distributed according to concentrated, dispersed and regular urban areas, with lower average unit values. Cattle manure has a diffuse distribution associated with production and storage sites as well as associated animal forage/feed productions. Actually, current cattle manure production does not correspond to current and real availability and exploitability for biogas production.

Under the tested conditions, the available and modelled data showed that, in this case, a higher quantity is produced and available of dairy cattle manure than sewage sludge.

3.2 ENVIRONMENTAL, SOCIAL AND ECONOMIC CRITERIA IN BIOGAS PLANT LOCATION

Environmental, social and economic criteria overlay and weighted product (AHP), followed by consistency and sensitivity analysis, indicate several suitable locations with low and medium altitude showing high suitability and adequate area requirements for collective biogas facility location (Figure 2). The results also pointed out a significant extension of exclusion areas, considering legal (e.g., master land use plans) and technical constraints (e.g., building implantations). Even when considering changes in weighting and the use of more restricted criteria (sensitivity analysis), it is possible to identify scattered locations with very high/optimum suitability and minimum area needs to locate biogas facilities (Figure 3).

Figure 2. Population density (inhabitants km^{-2}, dairy cattle farms (number) and biogas production facility location suitability.



3.3 BIOGAS FACILITIES' LOCATION, RESOURCES ALLOCATION AND PRE-DIMENSIONING

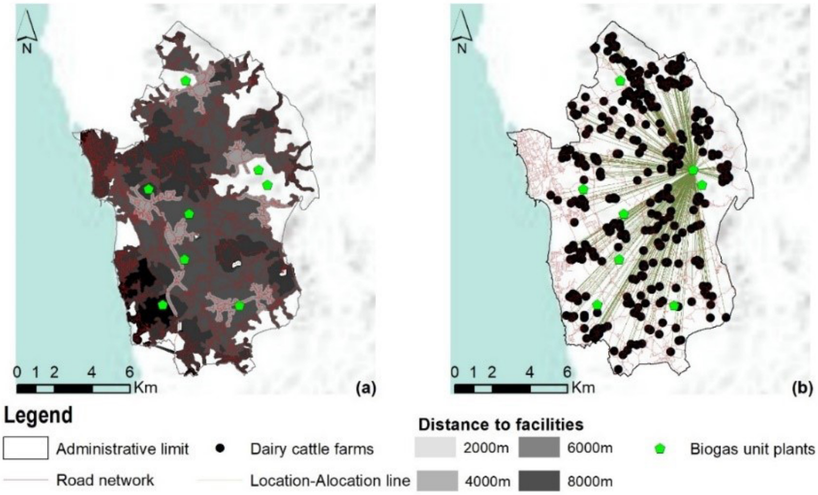
The modelling results refer to adequate local potential for the implementation of ACoD biogas production facilities considering local conditions, resources' spatiotemporal availability and the technical indicators about ACoD conversion processes and biogas caloric value (Table 1).

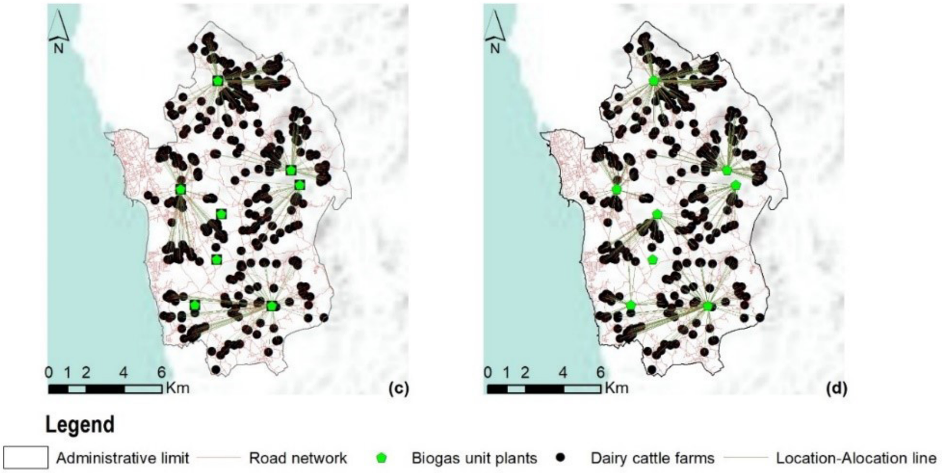
Table 1. Indicators adopted in the case study.

Indicators	Value	Reference
Volatile solids/Total solids (%)	65	[Coura *et al*., 2021]
Methane yield (mL gVS^{-1})	48.5	[Coura *et al*., 2021]
Biogas yield (mL gVS^{-1})	93.3	[Coura *et al*., 2021]
Average methane content (%)	52	[Coura *et al*., 2021]
Biogas calorific value (MJ m^{-3})	21.5	[Braun, 2007]
Waste sludge production (kgTS capita^{-1} year^{-1})	16.4	[GFA, 2000]

The spatially explicit model indicates a unique centralized biogas plant as a possible solution (Figure 3b), but also allows us to explore several scenarios/simulations regarding the number of facilities, dimension and location according to a multiobjective framework. In this context, as an example, two different scenarios were developed, i.e., decentralized systems with eight biogas facilities (Figure 4a) and centralized systems with five biogas production facilities (Figure 4b).

Figure 3. (a) Distance road analysis (m) to biogas plants; (b) Allocation analysis considering centralized (1 biogas facility); (c,d) distributed scenarios (5 and 8 facilities).



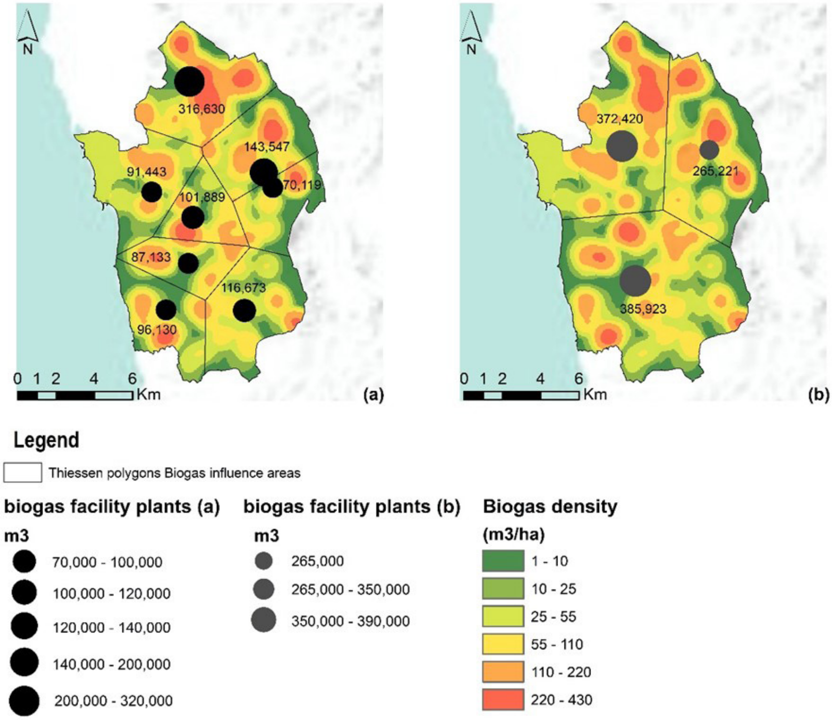


Local urban sewage sludge availability (853tonVS year−1) and dairy cattle manure (10,970tonVS year^{-1}) refer to a potential for biogas (1,102,773m^3 year^{-1}), methane (573,441m^3 year^{-1}), heat (7,046,717kWh) and electric energy (2,205,545kWh) production. The distributed system scenario revealed a maximum biogas production potential in the range of 70,000–320,000m^3 per facility per year. Assuming the indicators described in Table 1, the referred biogas potential production is equivalent to approximately 44,7300–20,4000kWh of heat energy or 140,000–640,000kWh of electrical power (Figure 4) per facility per year. In contrast, the centralized scenario indicates a maximum biogas potential production between 265,000 and 390,000m^3 per facility per year, which is equivalent to 1,600,000–2,600,000kWh of heat energy or 500,000–800,000kWh of electrical power. In the development, one of the centralized system scenarios (three biogas plants), which considered the existing WWTP biodigester (ETAR do Ave, Tougues), requires the construction of two new facilities (Figure 4).

These solutions considered different alternative projects and future biogas facility management models. Centralized system solutions reduce the initial investment, but reinforce the complexity and the costs of operation. According to [Thiriet *et al.,* 2020], centralized treatment plants have a significantly higher overall payload distance, which supports the idea of a higher transport efficiency of a decentralized system compared to a centralized one [Wang, 2014], even in a territory with a high density of urban and peri-urban areas [Thiriet *et al.,* 2020].

The present exercise and results also indicate the possibility of ensuring sectorial and territorial complementarity between urban and rural systems by assuming the adaptation of existing sanitation systems under territorial agreements/partnerships and innovative governance model frameworks. The spatially explicit model and the developed method can be tested and adjusted to other assumptions of the quantity, distribution and exploitability of available resources, as well as process changes/improvements and biogas production yields, in terms of quantity and quality (i.e., methane content in biogas).

Figure 4. Resource Allocation, Areas of Influence and Energy Capacity of the Biogas Facilities in the Two Scenarios.



4 DISCUSSION

Scientific and technological advances concerning bioenergy system plants' operation and the optimization of waste treatment and valorization result in knowledge with a major role to improve decision models regarding the location (at local or regional scale) and allocation resources to biogas facilities. The complex and dynamic nature of biogas production facility location, resources allocation and pre-dimensioning analysis requires multicriteria spatial models that consider environmental (protection), social (responsibility and safety) and economic (viability) criteria [Comber *et al.,* 2015], as well as conflicting and alternative location and allocation objectives, namely associated with centralized or distributed solutions.

The spatial, thematic, institutional and temporal scope of the study, as well as the selection of treatment and valorization systems, determines the issues, the nature and the development of the spatially explicit model. The developed approach and methods have a scale-based nature and are applicable to similar subjects, challenges and local spaces. The developed methodology and spatial model should consider changes in spatial and temporal patterns of available resources to produce bioenergy and process biogas yields. In this research, the biological treatment process kinetic indicators (Table 1) refer to the optimization of the AcoD of SwS and CMLF [Coura *et al.,* 2021], but the model's versatile nature allows the use of different kinetic parameters. In that regard, studies about the optimization of the AcoD process including other organic wastes/agroindustrial wastewaters, such as cheese whey, winery wastewater, among others, should be performed in order to obtain the kinetic indicators most suitable to be integrated into the model. Each research work case assumes specificities concerning the representation and meaning of environmental, social and economic criteria and objectives within a dynamic local political, legal and technical/technologic framework. The implementation of a biogas production utility, as a very complex infrastructure, may include pre/post treatments and must consider the logistics of sludge disposal. These aspects were initially considered in this research (i.e., weighted overlay – AHP) and are a subject to be thoroughly detailed and assessed, considering econometric and logistic aspects in the project's further phase.

The definition, weighting and interpretation of sensitivity analysis resulting from the application of spatial criteria should assume a multidisciplinary, collaborative and inclusive nature. Results location validation from in-field data and modelling outputs are central/critical to the biogas facility project's further phases. These scenarios and potential resource allocation data are relevant to the next steps of biogas production facility dimensioning (i.e., to calculate investment and operating costs, as well as the technical and economic viability assessment of each new biogas facility).

5 CONCLUSIONS

The modelling results pointed out that it is possible to set up the location of biogas plants based on resource availability and local biogas yield. Both data and the spatial model enable multidisciplinary approaches, analysis scale changes, actor coordination among the project/planning phases, as well as communication among stakeholders, technicians and the scientific community.

The developed spatial model indicates:

1. A high potential of local bioenergy resources available for biogas production (dairy cattle manure and sewage sludge) and the interest in complementing,

at a local scale, the use of existing biogas producing facilities (including those integrated in wastewater treatment plants) with new collective facilities;

2. The suitable locations for the installation of biogas production facilities in low altitude, forested areas, near to cattle farms, the road network and electric injection points, but far from the hydrographic network and avoiding the ecological reserves and protected areas;
3. The need to collect and analyze additional and detailed thematic and temporal (e.g., seasonal) data on sewage sludge and animal manure production;
4. The importance of developing multicriteria optimization algorithms to test a set of maximization and optimization functions (location and allocation issues), considering economic and econometric functions and objectives;
5. The reinforcement of multi-objective assessment to compare sites and alternative management models, considering investment and cost analysis.

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