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Review

The role of geospatial technologies for sustainable livestock manure management: A systematic review

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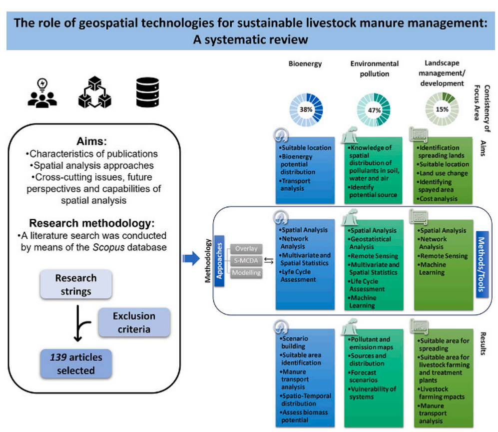
HIGHLIGHTS

- Spatial analysis can be of support for manure management sustainability.
- Three major focus areas are discussed: bioenergy, pollution and landscape.
- Spatial analysis is used with modelling, statistics, LCA, machine learning and MCDA.
- Bioenergy potential of animal manure remains a topic under investigation.
- Landscape management should be expanded to reduce nutrients pollution.

GRAPHICAL ABSTRACT



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ABSTRACT

Optimal livestock production is a key contributor to the achievement of sustainable development goals. The management and disposal of livestock manure is one of the main issues facing the sector in terms of soil, water and air pollution. Proper and sustainable management of livestock manure also requires a systemic approach to the problem, considering it at different territorial levels. In order to identify existing strategies to support this issue, this review investigated the use of Geographic Information System (GIS) analysis as a support for livestock manure management, highlighting the several GIS methodologies used to provide insight into the complexity, power, and potential offered by these approaches in study areas with different economic, social, and environmental variables, and to provide insights for future research. The study was performed on 139 papers chosen from a literature screening. Three study themes were identified by co-word analysis: Bioenergy, Environmental pollution and Landscape management/development, with a percentage division of research articles of 38 %, 47 % and 15 %, respectively. This study provides a theoretical and prospective framework for the long-term expansion of the livestock sector, which is critical to promoting a balance between sector development and environmental impact. The use of spatial analysis, along with additional tools and methods such as modelling,

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multivariate and spatial statistics, life cycle assessment, machine learning and multi-criteria analysis, has proven to be widely applied.

1. Introduction

1.1. Background

Various sustainable development goals of the 2030 Agenda (UN Department of Economic and Social Affairs Sustainable Development, 2015) support the sustainability of the livestock sector and associated practices. In particular, there are actions aimed at ensuring sustainable water management by eliminating uncontrolled discharge practices and minimizing the release of hazardous substances and materials. On the other hand, other actions are aimed at increasing, expanding, and strengthening the cost-effective and sustainable energy production systems, as well as initiatives for reducing emissions and mitigating climate change, including the transition towards more sustainable production models. As a result, it is of the utmost importance to implement innovative livestock and manure management methods (Varma et al., 2021). Examining these challenges from a spatial standpoint, by mapping possible criticalities and optimizing management, can help both farmers and decision-makers. Geographical models can surely provide insight about mutual connections and understanding of natural and social systems (de Oliveira et al., 2023a). As several authors have shown, a geospatial technology with a variety of approaches, objectives, and methodologies considerably supports livestock farming-related activities, such as the optimal siting of biogas plants (Levstek and Rozman, 2022) or avoiding contamination for non-point source of pollution (Hou et al., 2017). Geographical Information Systems (GIS), integrated with multivariate analysis or the Multicriteria Decision Analysis (MCDA) can also provide a more in-depth and informed perspective into spatial decisions. They have proven to be useful tools in various effluent management applications, particularly for the bioenergy sector, for assessing the environmental impact of the agronomic use of livestock manure and detecting soil contamination from various sources.

1.2. Significance of the research

Biogas generation is an important manure management system on animal farms, and its performance is determined by various factors (Onwosi et al., 2022). For the development of bioenergy, key considerations include social acceptance, economic aspects, and environmental impact components (Ferrari et al., 2022). In fact, according to several authors, geographical data and factors play a crucial role in identifying optimal sites for biogas plants, whether fed by livestock manure alone or cogenerated with other materials. They also help assess the biomass availability to feed the plants, transport distances, and environmental restrictions in a given area (Venier and Yabar, 2017; Guler et al., 2022; Díaz-Vázquez et al., 2020). Regarding the environmental impact of animal manure, the rapid development of livestock farming, and the agronomic use of livestock manure, are leading to excessive nutrient loads impacting soil, water, and air quality (de Vries et al., 2021; Zhuang et al., 2020). The high concentration of farms in a specific area and subsequent pressure on agricultural areas necessary for sustainable agronomic use of livestock effluent can lead to an excess of nitrogen (N), phosphorus (P), chemical oxygen demand (COD), heavy metals (HMs) (Wang et al., 2021), antibiotics (Ant) (Rashid et al., 2023), faecal bacteria (Trevisan et al., 2010) and oestrogens release (Liu et al., 2014) in both soil and water. Moreover, manure is the primary source of nitrous oxide (N_2O) and methane (CH_4) emissions (Tibbo and van de Steeg, 2013). Excessive use of nitrogen fertilizers significantly contributes to N_2O emissions from agricultural soils and ammonia (NH_3) from animal housing and storage tanks. Finally, regarding contamination detection, GIS approaches have been confirmed as useful tools for investigating soil and water pollution from the already mentioned contaminants (Hou et al., 2017). Additionally, these approaches can support fertilization activities by providing knowledge on the spatial variability of agronomic characteristics of soil nutrient status (Momtaz et al., 2017; Fu et al., 2010). In the current literature, there is a clear multidisciplinary approach linked to the use of spatial analysis or strategies to support livestock manure management, highlighting its potential. Therefore, a literature review on this topic is essential to fully understand and clarify the current state of the art and to identify the different approaches and methodologies used in different contexts. Furthermore, to our knowledge, no current literature review describes the potential of this tool and the methodologies used by different authors.

Based on the existing knowledge, this review paper aims to give a comprehensive account of applied geospatial technologies as support for manure management and environmental pollution analysis. Specifically, the primary research questions driving this comprehensive review analysis are: i) How is spatial analysis used in manure management? ii) How can spatial analysis support livestock manure management?

To this purpose, the following aspects have been considered:

i) The main characteristics of publications are analysed, including production countries' annual publication rate, journal, publication phase, co-word and popular research topics;
ii) The spatial analysis approaches, methodologies and uses are discussed with reference to the various application areas, focusing on the potential impact on the livestock sector and spatial planning of agro-livestock systems, and the more horizontal, recurrent and specific aspects;
iii) Cross-cutting issues, future perspectives and potentials of spatial analysis in promoting sustainability in the livestock sector are identified.

2. Methodology

2.1. Research strategy

Since *Scopus* indexes more citations of peer-reviewed literature than any other database and is regarded as the world's biggest scientific literature review database, it was selected for searching articles relevant to the research subject (de Oliveira et al., 2023b). A literature search was conducted using the strings provided in Table 1.

Each string identifies a specific field, i.e. string *#1* included the different types of livestock, string *#2* included the different spatial

Table 1
Research strings.

String		Search within	Keywords
#1		TITLE-ABS-KEY	"animal farm*" OR livestock OR "livestock farming" OR cattle OR cow OR pig OR swine OR buffalo OR poultry OR broiler OR dairy OR beef OR sheep OR goat OR rabbit
#2	OR	TITLE-ABS-KEY	"spatial multi-criteria" OR "multi-criteria analysis" OR GIS OR "geographic information system" OR "land suitability" OR "spatial analysis" OR "spatial MCDA" OR "geospatial analysis" OR "remote sensing"
		TITLE OR AUTHKEY	"spatial distribution"
#3		TITLE-ABS-KEY	manure OR slurr* OR excreta OR dung OR urine OR biogas

analysis approaches and methods, and string *#3* included the different livestock by-products which has been combined with an 'AND' operator. The choice of this string subdivision was obtained through a preliminary analysis involving the inclusion of various keywords related to or associated with the livestock sector. This preliminary analysis made it possible to identify keywords that were redundant and misleading and that caused search weighting and bias. In addition, a keyword related to digestate, i.e. *biogas*, has been added to string #3. This choice is based on the issue that the word digestate may refer to a field of study not related to livestock manure. The asterisk (*) was used to replace a group of characters (e.g. *slurr* = slurry or slurries*); instead, the quotation mark ("") operator was utilized to search for specific keywords or phrases. In this context, string #2 has been split into two parts to ensure the search is targeted. Indeed, the keyword *"spatial distribution"*, being generic, leads to results that are not relevant to the topic of the analysis. Consequently, it was considered in the title and author key, in order to be more targeted. The search was limited to articles published in the last 15 years (from 2009 to April 2023) and written in English.

A total of 315 articles were identified and downloaded. Their metadata were exported to Microsoft Office Excel software and analysed to determine the state of the art in the application of spatial analysis to manure management. The articles served as a basis for gaining insights into the current trends and research gaps in this area.

To ensure the inclusion of the most relevant and useful information, a set of exclusion criteria was established for analysing relevant articles (Fig. 1). These criteria included: (a) papers not related to manure management; (b) papers with abstract only and (c) papers without spatial analysis or with spatial analysis at the plot level. The review of the articles was carried out manually by examining the content of each article.

2.2. Bibliometric analysis

The analysis was performed by focusing on several aspects, including geographic area, publication frequency, journal, publication phase, co-word and focus areas of spatial analysis. The analyses were performed using Microsoft Office Excel software (version 2023), with the exception of the co-word analysis which was performed using the open-source VOSviewer (version 1.6.18) (Van Eck and Waltman, 2018).

2.2.1. Geographic area, publication frequency and journals analysis

To identify geographical areas where the spatial analysis as support to livestock manure is most commonly applied, the selected articles were grouped by country, based on the study area. Microsoft Excel's mapping function was applied to plot the publication study areas of each article. The geographical area analysis aimed to determine how often a particular country was studied. In particular, we found three papers that had the European territory as the study area and one paper devoted to the USA and Turkey at once. In the first case, all the countries belonging to the European territory were assigned a starting value of 3, in the other case USA and Turkey were assigned a value of 1. To understand the trend and frequency of publication since 2009, the articles were classified by year and cumulative publication was also reported. Furthermore, an analysis was carried out to identify the journals with more publications on the topic highlighting those with more than two published articles.

2.2.2. Publication phase analysis: S-curve

To evaluate the development status of literature on the application of spatial analysis in livestock manure management, the *S-curve* model was applied (Mao et al., 2021; Hollas et al., 2022). The model has been applied up to the year 2022. Since the bibliographic analysis was undertaken in April 2023, data from 2023 were excluded because the year was not yet complete. This model divides the given trend topic into four phases: Emergence, Growth, Maturity and Senility. The equation (Eq. (1)) was used:

$$NA_t = \frac{NA_{max}}{1 + e^{-\alpha(t-\beta)}} \tag{1}$$

where NA_t represent the dependent variable of the curve, i.e. number of cumulative publications per year, t represents the time variable, α and β are parameters of the model and NA_{max} is the maximum expected publication for this trial.

The number of cumulative publications curve was fitted with the model by means of the Microsoft Excel software, with an associated 95 % confidence level Residual sum of squares (*RSS*) (Eq. (2)), root mean squared error (*RMSE*) (Eq. (3)), and determination coefficient (R^2) (Eq. (4)) were used to test the model fitting the experimental data:

$$RSS = \sum_{i=1}^{N} \left(y_{prd,i} - y_{Act,i}\right)^2 \tag{2}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(y_{pdr,i} - y_{Act,i}\right)^2} \tag{3}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} \left(y_{prd,i} - y_{Act,i}\right)^2}{\sum_{i=1}^{N} \left(y_{prd,i} - y_m\right)^2} \tag{4}$$

where $y_{prd,i}$ and $y_{Act,i}$ are the predicted and real values, y_m is the average value, and N is the total number of estimates (Scotto di Perta et al.,

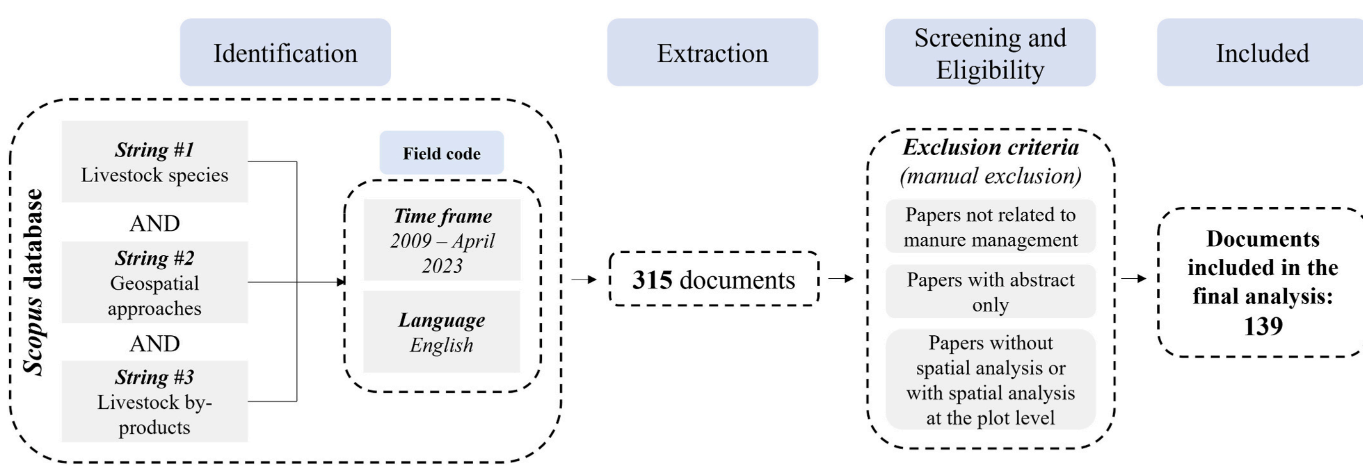

Fig. 1. The research framework.

2022).

2.2.3. Co-word analysis

The keywords of each publication were analysed and visualized using VOSviewer, free and open-access software that provides bibliometric maps (Nicu and Fatorić, 2023; Catumba et al., 2023). This analysis allows for thematic clustering, visualization of relationships through a combination network, and relevance of the different keywords (Donthu et al., 2021). The most common keywords in the literature can also be found using the size of the label or circle that results from visualizing the results of the keyword recurrence analysis; the wider the node, the greater the recurrence (Van Eck and Waltman, 2018). The analysis also provided data on link strength and allowed for identifying the main clusters indicated as *Focus areas* for further investigation. The type of analysis performed was co-occurrence of author keywords, with a minimum number of keyword occurrences of four. To focus on methods and approaches, the keywords *"GIS"*, "*Geographical Information System"*, "*Geographic Information Systems"* and "*Geographic Information System"* were excluded from the analysis, as they represent a common tool for all the papers under review. In addition, the keyword *"Bioenergy"* was changed to *"Biogas"* as the topic was related to anaerobic digestion. This analysis produced 13 keywords that met the threshold, with a total link strength of 58 and 3 thematic clusters with headings based on recurring keywords and associations. Clustering the results of the keyword recurrence analysis helped to identify and organise the main themes found in the literature reviewed. The keywords that frequently co-occurred allowed for the identification of three clusters, named after the topic of interest to which they relate (Focus Area), as indicated in the following section.

2.2.4. Focus area

Spatial analysis for livestock manure management is an important aspect of research that has received considerable attention in recent years, according to different thematic areas of expertise. Thus, the selected articles were categorized, based on the results of the co-word analysis done on the keywords, namely *Bioenergy*, *Environmental pollution* and *Landscape management/development.* The approaches and techniques used to achieve the aims of the selected literature are discussed for each focus area in Sections 3.4.1, 3.4.2 and 3.4.3.

3. Results and discussions

After applying the exclusion criteria to the search results, a total number of 139 papers covering the last 15 years of research were selected for the final analysis. These papers were divided into different categories as follows: 126 *research articles*, 4 *reviews,* 6 *conference papers* and 3 *book chapters*. This section presents the results of the bibliometric analysis based on geographical, time and source distribution, keywords and focus area.

3.1. Geographical area, publication frequency and journal analysis

Fig. 2 shows the distribution of the publications' study areas. As shown, among the most productive countries, China leads the way with 30 papers, closely followed by the United States with 21 papers. The European continent has a well-distributed examination of areas, but Africa appears to be understudied.

The highest number of publications was between 2021 and 2022, with a total of 21 and 17 publications, respectively (Fig. 3), representing

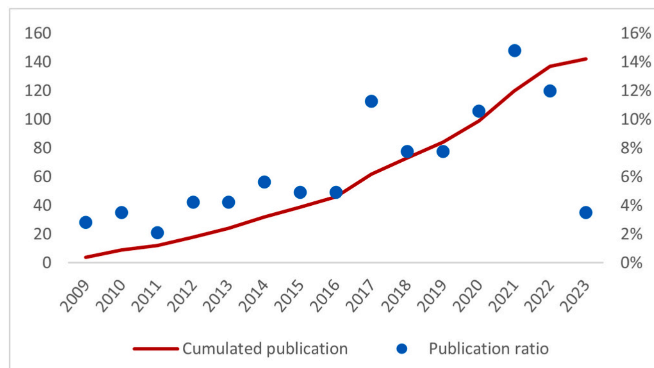

Fig. 3. Publication frequency.

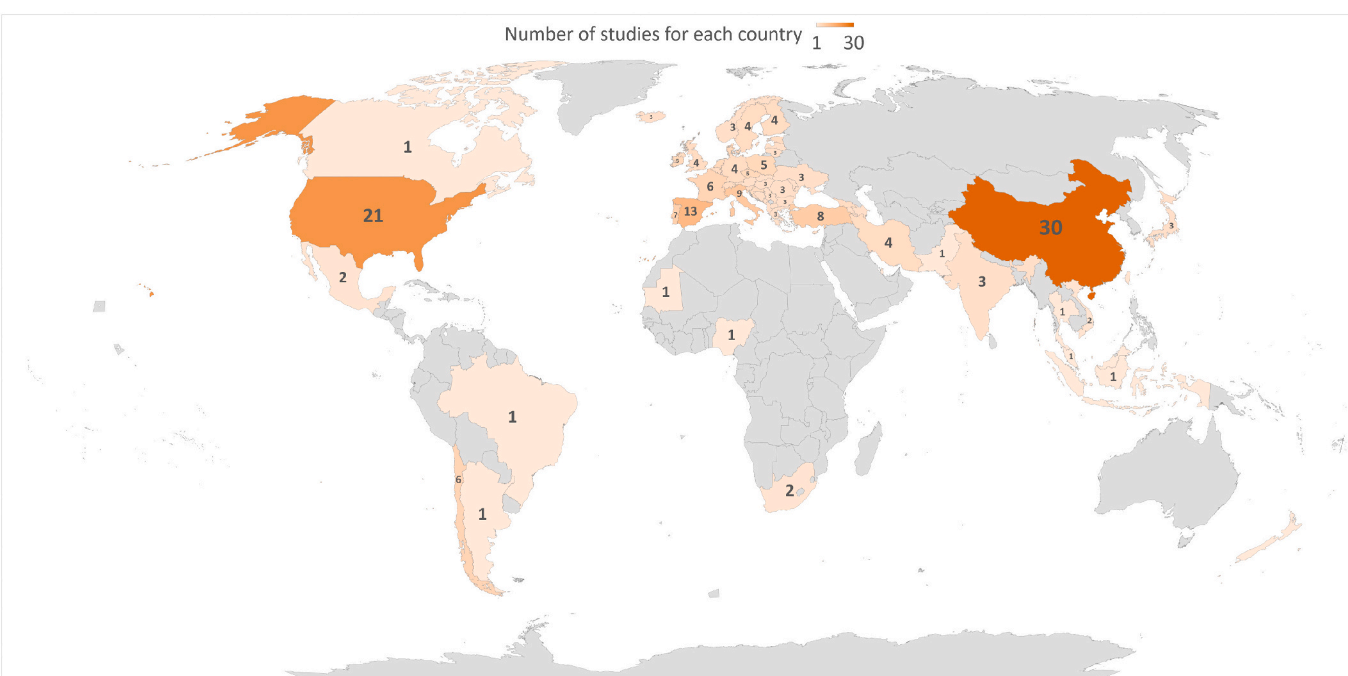

Fig. 2. Distribution of publications by country.

a meaningful increase in the amount of research and literature produced compared to previous years. Furthermore, over half of the analysed publications were published within the last seven years (2017 to 2023). This indicates an active and growing field of study, based on a recent increase in research output.

A total of 12 journals met the threshold of at least three articles published, accounting for 40 % of the research output with 57 articles (Table 2). The journals *Science of the Total Environment* and *Journal of Cleaner Production* have the highest number of papers published. In addition to the number of articles published, the CiteScore, a metric that measures the impact or reputation of the titles in the journal, was reported. The journals that have emerged with a higher CiteScore are *Renewable and Sustainable Energy Reviews* and *Resources, Conservation and Recycling.*

3.2. Publication phase analysis: S-curve

The curve that resulted from Eq. 1 was divided into four sections: Emergence (I), Growth (II), Maturity (III) and Senility (IV). The trend analysis of publications on the application of spatial analysis to livestock manure management is shown by the S-curve in Fig. 4. This curve also depicts the knowledge on the topic, which culminated in 2021 with 117 publications since 2009, as influenced by a change in livestock manure management in policies related to the topic. This can be justified by the growing interest in increasing the sustainability of livestock production around the world, improving and identifying new strategies and approaches through spatial analysis. The S-curve shows that the research has reached a maturity level, which indicates a thorough understanding of the subject. Therefore, the evaluation presented in this review article can provide comprehensive insights into the topic's current strengths and limits, as well as outline of potential further scenarios in future research.

3.3. Co-word analysis

The keyword analysis resulted in the division of the "author keywords" into 3 thematic clusters, 14 items and 33 links (Fig. 5a and Fig. 5b). In a network or overlay visualization, each node represents an entity, which in the case of Fig. 5a and Fig. 5b, represents a keyword. The size of the node indicates the number of occurrences of each keyword. The link between the nodes represents the co-occurrence of the keywords, which means that they often appear together. The frequency of these co-occurrences between keywords is indicated by the thickness of the link.

Thematic cluster *Bioenergy* (shown in green colour in Fig. 5a) contains the resulting keywords *"biogas", "manure", "spatial analysis", "anaerobic digestion"* and *"renewable energy"* each one with a total link strength of 21, 20, 14, 13 and 9, respectively. The most commonly appearing word was determined to be *"biogas"* (27 occurrences), followed by *"manure"* (14 occurrences). The keyword *"biogas"* is a topic that has been studied by many authors recently (Prado et al., 2018; Yan et al., 2022; Yalcinkaya and Ruhbas, 2022); in fact, a large number of papers are based on this type of topic, furtherly supporting the *bioenergy*.

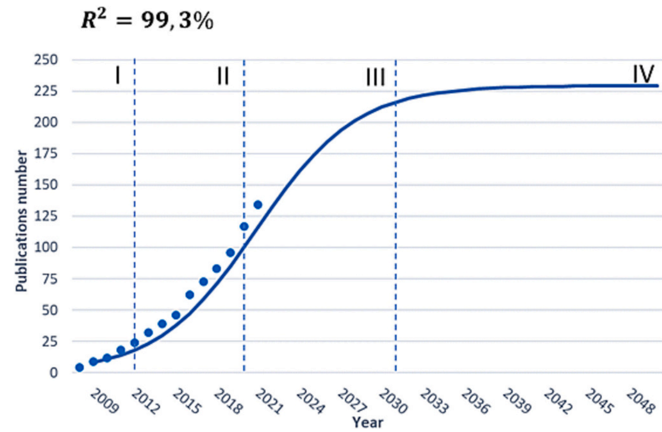

Fig. 4. S-curve.

Thematic cluster *Environmental pollution* (shown in red colour in Fig. 5a) includes the resulting keywords *"nutrient management", "agriculture", "nitrogen", "livestock"* and *"methane"* each one with a total link strength of 6, 5, 5, 4, and 1, respectively. The keywords *"nitrogen"* and *"nutrient management"* belong to the same cluster probably because they are linked by the fact that proper nutrient management is important to avoid the negative effects of nutrients, especially N, which is responsible for the eutrophication of water and the emission of NH_3 (de Vries et al., 2021).

Thematic cluster *Landscape management/development* (shown in blue colour in Fig. 5a) includes the keywords *"livestock manure", "spatial distribution"* and *"carrying capacity"* each one with a total link strength of 10, 6 and 2, respectively. This group, as shown in Fig. 5b, along with the *Environmental pollution cluster* contains the recently used words found in the selected articles. The keyword *"carrying capacity"*, with 4 occurrences, is one of the most recent topics and may indicate future research. It is understood as the carrying capacity of an agricultural area for nitrogen, i.e. the maximum input of kg N/ha (Wen et al., 2021) or its ability to absorb animal excreta in a given time frame (Wu et al., 2022). The carrying capacity of a given study area or scale can also be determined by livestock density or forage availability, as described by Li et al. (2021). This cluster also includes *"spatial distribution"*, which had a recurrence of 14, one of the most significant terms in the selected body of literature.

Table 2
Major journals.

Journal	Docs No.	Docs %	CiteScore[a]
Science of the Total Environment	11	8	16.8
The Journal of Cleaner Production	8	6	18.5
Renewable and Sustainable Energy Reviews	6	4	26.3
Journal of Environmental Management	5	4	13.4
Environmental Science and Pollution Research	4	3	7.9
Journal of Environmental Quality	4	3	6.6
Renewable Energy	4	3	16.1
Biomass and Bioenergy	3	2	10.8
Environmental Pollution	3	2	14.9
International Journal of Environmental Research and Public Health	3	2	5.4
Resources, Conservation and Recycling	3	2	20.3
Sustainability (Switzerland)	3	2	5.8

[a] The CiteScore depends on the number of citations and the number of articles published in the last four years (de Oliveira et al., 2023a).

3.4. Focus areas

As already reported in Section 2.2.4, the present review was divided into three different focus areas (Fig. 6) based on the results of the co-word analysis: *Bioenergy*, *Environmental pollution* and *Landscape management/development*. The main specific goals, approaches, methodologies and techniques used in each focus area are described in the following sections. The studies in this focus area present a methodological framework, which is summarized in Fig. 6.

3.4.1. Bioenergy

The main theme of the articles reviewed in this area is biogas production, and the papers have two main goals: i) identification of optimal sites or areas for new plants and analysis of the costs associated with transporting the effluent to the plants; ii) assessment of biomass distribution and bioenergy potential of a study area.

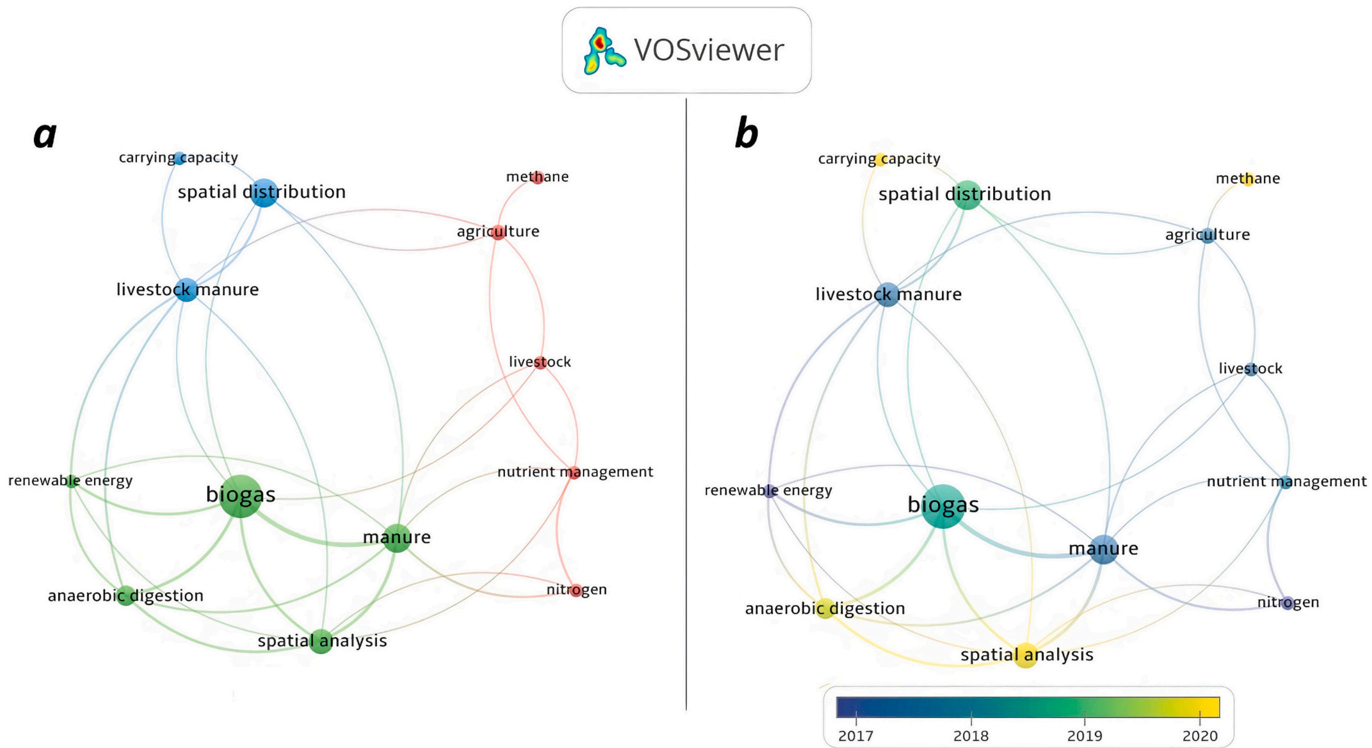

Fig. 5. Maps of Keyword correlation (a) and Keyword timelines (b).

All the works (Table S1) start with identifying the study area, followed by data collection and creating a geodatabase (Prado et al., 2018). Data collection and processing mainly include farms or biomass sites, administrative boundaries, municipality location, digital elevation model, hydrographic structure, agricultural land use map and roads (Díaz-Vázquez et al., 2020). Each study area has a variety of policy aspects and strategies that are crucial to be understood (Guler et al., 2022). Analyses are carried out using the different software, listed in Table S1 in Supplementary Materials, which shows that ArcGIS was the most used (>50 %). Articles for which the software was not specified were categorized as *'Not specified'*.

3.4.1.1. Siting of bioenergy facilities. This type of analysis is used at different scales/landscape levels (Table S1), but is mainly applied at National, Regional and County levels. Identifying areas suitable for renewable energy plant installation is a complex matter and requires combining multiple techniques, strategies and tools (Fig. 6). Several studies propose an integrated approach combining GIS techniques with multi-criteria analysis (Sandra Silva et al., 2017a). The first step in this analysis focuses on the different criteria or indices used (B. Yan et al., 2021a; Guler et al., 2022). The literature analysis reveals that there are three categories of criteria that can be represented spatially: environmental, social and economic. For instance, Guler et al. (2022) use seven criteria, including slope and proximity to water, roads, railways, green areas, built-up areas and airports. Moreover, Dao et al. (2020) sketch out transport networks, land use, surface water, protected areas, surface water and airports as restriction criteria. In both cases, these criteria are used to delimit the areas suitable for plant implementation and are clustered in three different groups. The use of buffer zones with GIS is applied as exclusion criteria to avoid proximity. Based on national construction standards for buildings and commercial infrastructure and literature sources from previously published studies, buffer zones are used for the different restriction factors (Dao et al., 2020; Venier and Yabar, 2017). Buffer zones limits can vary from one study to another. For example, Dao et al. (2020) use a buffer of 30 m for transport networks and 200 m for surface waters, while Sliz-Szkliniarz and Vogt (2012) use 10 m and 50 m for transport networks and surface waters, respectively. Economic criteria can also involve material accessibility, as demonstrated by Dao et al. (2020), who assess collecting efficiency, safety, and cost minimization. Coura et al. (2021), assign a higher appropriateness rating as the distance to farms decreases. Among the main factors mentioned by Yalcinkaya (2020) is the availability of biomass (livestock manure and organic fraction of municipal solid waste (OFMSW)). The choice of criteria can influence the suitable site for different study areas differently. For this reason, the Multi-criteria Decision Making (MCDM) methods were used to give them different weighted. The MCDM methods are considered strategic support in making decisions. Several spatial multicriteria decision methods have been used in bioenergy facility siting studies (S. Silva et al., 2017b), with fuzzy spatially explicit multicriteria decision systems using the Analytical Hierarchy Process (AHP) being the most common. It is possible to calculate the weighted preferences or the importance of criteria with the help of the AHP (B. Yan et al., 2021a; Cervelli et al., 2021). AHP, developed in the 1970s by Thomas L. Saaty, is a method used for organising and analysing complex decisions, using mathematics and psychology. Using pairwise comparisons, it provides measures of consistency between judgements, prioritizes criteria and alternatives, and simplifies preference evaluations between decision criteria. Gital Durmaz and Bilgen (2020) use the results of the integrated approach between GIS and AHP to develop a model that aims to maximise profit and minimise biomass transport distances. In the case of Guler et al. (2022), the Best Worst Method (BWM), combined with fuzzy logic, was chosen for the assignment of criteria weights thanks to its fast processing time and the consistency of the results. The results give each parameter a suitability value from 1 to 5, with lower values indicating low risk and higher values indicating low feasibility (Díaz-Vázquez et al., 2020). In this case, the weighted overlap analysis was used. In order to obtain a suitability map, these analyses are necessary (Yalcinkaya, 2020). Another approach is that of Zareei (2018), which involves the production of a map showing the preferred areas for installation. This was produced from data on the availability of livestock manure and rural waste. Data georeferencing and the waste spatial density distribution

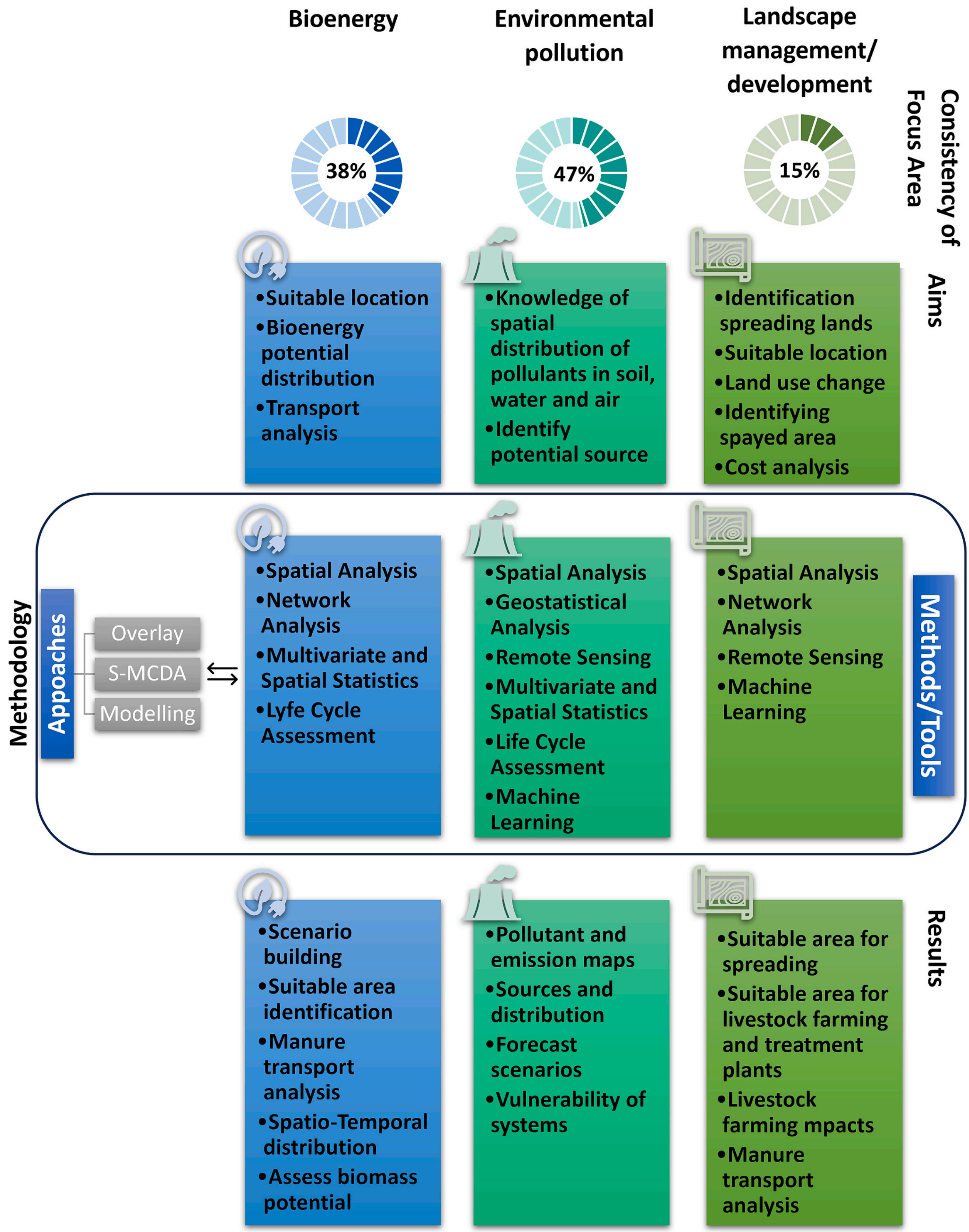

Fig. 6. Focus Area and framework methodology.

were processed. CH_4 production maps were calculated and combined with land use maps, including constraints, i.e. legally protected areas, to produce the final map showing the different scales of the area's suitability. In fact, some studies do not provide a precise location point but show a preliminary identification of the most suitable areas (Sliz-Szkliniarz and Vogt, 2012). Areas with easy access to electricity and gas distribution networks, represented by applying a 2 km buffer to these networks, and areas with a high density of manure within a 10 km radius of each farm, chosen to make transport advantageous, represent areas with greater development potential.

In other cases, among the methods/tools depicted in Fig. 6, a function of the Network Analyst tool, available on ArcGIS, is used to locate the plants (Yabe, 2013). Many studies present a Network Analysis, starting from the spatial distribution of farms, in these cases the geographical centre of each farming community is considered, which is shifted to the nearest roads. Candidate sites are then selected according to soil suitability/land uses: natural land, cultivated meadows, structured land for construction, etc. Finally, suitable locations for the installation of the facilities are obtained using a minimisation function for the number of facilities, defining a maximum distance of 10 km between the farming community and the facility. A similar approach was taken by Thompson et al. (2013a), who used the Network Analyst tool, which was applied to suitable areas derived from a preliminary analysis. Starting from the location-allocation function, the optimal location is defined as the one that collects the maximum number of dairy farms that can supply the effluent, placed at the maximum distance, ensuring a ratio of energy output to input (defined as vehicle capital, labour and fuel costs for manure transport) of <1, meaning a positive energy return on the supply chain. This analysis involved the application of exclusion criteria (sensitive areas) and inclusion criteria (proximity to electricity distribution infrastructure) in combination with the availability of biomass from dairy farms.

The optimal location of biogas plants also depends heavily on the distance between farms and the plant. These transport networks must be short, both in terms of length and time and economical (Worawimut et al. 2020). Transport distance is an important factor as it affects the cost of raw materials and biogas production. Scarlat et al. (2018) suggest that for materials with a high dry matter content (70 %), a transport distance of up to 50 km is feasible. However, for materials with a low dry matter content, such as slurry manure, it is advisable not to exceed 10 km. This choice was related to and conditioned by the fact that biomass or livestock farms are scattered over large areas with varying availability. Brahma et al. (2016) developed a transport model that optimises transport costs, which also depend on the type of vehicle used. Three types of roads are often considered, the characteristics of which need to be known: (i) national highways, (ii) main roads and (iii) rural roads, depending on their suitability for transport. On costs and distances assessment, the length and speed limits of each road type play a crucial role in determining the process accuracy. Other types of transport are not taken into account. The analysis is carried out using the Network Analyst tool in ArcGIS. The Closest Facility solver (Network Analyst) measures the travel costs between the incidents (livestock farms) and the facilities (biogas plant) and determines which are closest to each other (Soha et al., 2021). When the *closest facilities* are searched, it is possible to specify how many are wanted, and it shows the best routes between the events and the facilities, as well as return routes. Another tool, based on the road network, is the *location-allocation function*, which allows the correct source of biomass to be identified (Yalcinkaya, 2020).

Finally, as illustrated by the framework (Fig. 6), some works use the modelling approach. Levstek and Rozman (2022) created a model by intersecting and combining numerous input factors to locate and pick ideal positions; these parameters can be changed to ensure the model's applicability in other areas. The model inputs are spatial (the location of farms and food establishments, together with the amount of waste produced by each), energetic (biogas and waste energy potential), and economic (investment and economic variables). In the study by Casas et al. (2021), an algorithm was created to evaluate the net present value of the plant using an optimization model, with the goal of determining the most profitable configuration. Hoo et al. (2019) used BeWhere, a Mixed Integer Linear Programming (MILP) model whose aim is to reduce production costs and carbon emissions, to identify the ideal production and location of biogas facilities. A 10 km × 10 km Grid Index Feature was developed in this study to visualize the spatial distribution of the energy content of the materials feeding the plant as well as the biomethane demand generated from natural gas demand. Each grid can represent a prospective site determined by the construction of an origin-destination cost matrix based on the road network.

3.4.1.2. Assessment of biomass distribution and bioenergy potential. Knowing the types of manure or slurry (cattle, pig, poultry, sheep/goats etc.) and quantities of biomass available are the key data for conducting this analysis. This information is obtained from various databases (Díaz-Vázquez et al., 2020) or using statistical (Guler et al., 2022) or cadastral data (Golubić et al., 2019). GIS software is then used to estimate and map the theoretical biogas potential of the available biomass and potentially recoverable methane (Scarlat et al., 2018). Understanding the spatial distribution of biomass and bioenergy potential is crucial for assessing the future development of potential biogas production and knowing the current status of a given area. The distribution of farms, and therefore of biomass, is very heterogeneous spatially, so it is important to evaluate the use of spatial analysis to identify advantageous and prosperous areas for biogas production. Ferrari et al. (2021) therefore use spatial statistical tools (Fig. 6), including the Moran I index, and apply them to animal density, nitrogen load and potential methane production, calculated from the different types of animals. Spatial autocorrelation, also applied to farms as demonstrated by Venier and Yabar (2017), allows to understand the extent to which neighbouring objects are similar. In fact, in a map, positive spatial autocorrelation occurs when there is a grouping of similar values, otherwise, there is negative spatial autocorrelation (Venier and Yabar, 2017). In some studies (B. Yan et al., 2021b; Bojie Yan et al., 2021), an emerging hotspot analysis was carried out, which identifies statistically significant spatial clusters of hot and cold spots using the Getis-Ord Gi* statistic available in GIS software. This analysis makes it possible to identify locations that need to be prioritised in a decision-making process (Yalcinkaya and Ruhbas, 2022). The Focal Statistic-sum tool in the Spatial Analyst toolbox is also used to identify the areas with the highest density of livestock effluent, with a specific buffer to identify the associated farms, Sliz-Szkliniarz and Vogt (2012) use a 10 km buffer. The high availability of biomass to feed biodigesters can also be mapped using the Inverse Distance Weighting (IDW) method, available in the Spatial Analyst tool of ArcGIS (Yalcinkaya, 2020). This method estimates the amount of biomass available at a given position based on a weighted average of the biomass coming from each mapped farm, where weights decrease with distance.

3.4.2. Environmental pollution

3.4.2.1. Soil pollution. Among the articles belonging to this sub-area, 13 articles use interpolation and density methods, as shown in Table S2. Before discussing the approaches used, it should be noted that the first cardinal step in this type of analysis concerns the knowledge of the site, in particular the sampling points that represent the starting point of the analysis.

In particular, a soil contamination index was calculated and interpolated (IDW), depending on the concentration of each heavy metal (HM) and the number of HMs detected in the same sample, and several hot-spot areas were identified, suggesting areas that should be targeted to protect food safety. Kriging is the most commonly used method, particularly in field-scale conditions where factors such as climate and geology are homogeneous, as it provides an unbiased prediction and an estimate of the variance of the prediction (Fu et al., 2010). Unlike IDW, kriging is based on statistical and geostatistical models and provides stochastic interpolation. In several studies, Kriging is used in combination with multivariate analysis techniques (Fig. 6), in particular, Principal Component Analysis (PCA) and Cluster Analysis (CA) (Zhang et al., 2016; Sun et al., 2017; Zhuang et al., 2020). These are used to identify correlations between heavy metals or to identify anthropogenic sources of HMs (Jiao et al., 2018). Similarly, Kriging is used to simulate the spatial distribution of antibiotics used for disease control and growth promotion in intensive livestock production to assess potential ecological risks from contamination levels. To monitor environmental conditions in a 600 km^2 area in Gunnan County, Sun et al. (2013) took 2400 samples and produced geochemical maps. Geostatistical techniques (Fig. 6), mainly Kriging (Momtaz et al., 2017) and Trans-Gaussian Kriging (Fu et al., 2010; Fu et al., 2016) can also be used to describe, examine and interpret the spatial variability of some important agronomic soil properties in order to suggest, through detailed maps, site-specific agronomic management by reducing nutrient and pollutant inputs from fertilizers and manure.

Density tools are used to calculate the density of input features within a neighbourhood around each output raster cell and create density maps, i.e. maps where the magnitudes of the values are distributed in a given circular area around a position of known value. To investigate the susceptibility of cropland and pasture soils to antimicrobials in manure applied to the field, Bueno et al. (2022) used data from farms in Minnesota (actual farm locations) and the effluent produced on each farm applied to the field. Experts' advice was used to determine the distance of manure application from the field, as no such data were available in the literature. This distance was then used as a search radius around the centre of each farm to apply Kernel Density (KD), a function of the Spatial Analyst tool in ArcGIS. García et al. (2022) also used KD to analyse soils, particularly intensive crops and pastures, with high, medium or low manure loads. The parameter ‘search radius’, expressed in km, was defined by a rule of thumb as follows (Eq. (5)):

$$Search\ radius = 0.79 * min\left(SD, \sqrt{\frac{1}{ln(2)}} * D_m\right) * n^{-2} \right) \tag{5}$$

where SD is the standard distance, D_m is the median of the distance and n is the total census.

In the other papers analysed, various methods and approaches (Fig. 6) are used to analyse the problem relative to antibiotics, HMs, N, P and COD (Wang et al., 2021; Rashid et al., 2023; Nesme et al., 2015). In the area of the release of antibiotics into the soil, which mainly occurs when livestock manure is applied as fertiliser, other works use different approaches to risk assessment (Zhang et al., 2022; De La Torre et al., 2012; Rashid et al., 2023). As in the case of De La Torre et al. (2012) carried out a Europe-wide risk assessment analysis. This analysis consists of 4 steps: i) Release assessment, which considers the amount of each active substance. Due to the lack of data on the use of veterinary medicines (VMP), it was assumed that the amount of antibiotics released into the environment is proportional to livestock production, derived from FAO data; ii) Exposure assessment, which depends on the potential for contamination, a function of the binding and retention rate of each antibiotic; iii) Consequence assessment, which aims to identify areas subject to exposure. These areas will be derived from geo-referenced land use information obtained from CORINE Land Cover (CLC); iv) Risk estimation, carried out using a spatial mapping technique, which generates maps by integrating the steps described above. The risk estimation considers that soil vulnerability requires the simultaneous presence of all three levels (release, exposure and consequences). Each parameter was represented by a layer with a grid size of 10 km, considering its geographical distribution. The 3 parameter layers were normalised and unified using Spatial Multi-Criteria Analysis (S-MCDA) to produce spatial maps showing the risk gradient from high to low. In order to identify the European provinces with significantly higher values than the others, a spatial analysis was carried out using the statistical tools available in ArcGIS.

Several articles assess the environmental impacts of key nutrients, including N and P. The main elements are the calculation of nitrogen and phosphorus balances and their spatial distribution (Hou et al., 2022; Liu et al., 2016; Jin et al., 2020; Pulighe et al., 2014; Yan et al., 2019). In the work of Cameira et al. (2019), they considered that the calculation of the N surplus depends on the sum of N from mineral fertilizers, livestock tributaries, irrigation water, atmospheric deposition, biological fixation and cultural residues, from which the uptake by crops must be subtracted, considering those representatives of the area studied. For livestock manure, the N lost through volatilisation and leaching is also considered. To assess the spatial distribution of inputs, outputs and N surplus in Nitrate Vulnerable Zones (NVZs) at a municipal level, the data were processed using GIS software (QGIS). Indeed, an effective solution for surplus N is proposed by Ghimire et al. (2021) who, through a spatial multiscale analysis considering different levels of crop-livestock integration, investigated whether available N from livestock can be assimilated by crops and pastures. Modelling the ability of agricultural crops to absorb nutrients (N) from manure was the aim of Porter and James (2020) who developed a manure application modelling programme using ArcGIS, also used by Dell et al. (2022). The approach is based on a series of cycles analysing 3 different scenarios, each with an assigned maximum transport distance. For each cycle, the nearest field with an N requirement >0 is identified for each farm by Euclidean distance. If a farm meets the entire N requirement of the field, the amount applied is subtracted from the farm's balance, and once this requirement has been met, the land is no longer suitable for receiving N. With each cycle, a new neighbouring field suitable for receiving manure is identified, with increasingly distant fields being intercepted. This programme is repeated until the barn or field has exhausted its N load and meets the requirements.

Liu et al. (2016) carried out a spatio-temporal analysis of the pollutant discharge coefficients of pigs, cattle, laying hens, meat poultry and sheep for total nitrogen (TN), total phosphorus (TP) and COD over a 20-year period, using the average annual growth rate (AAGR) as a factor to assess the change in livestock load in each province in China.

The proper management of livestock manure has also led to the development of Spatial Decision Support Systems (SDSS), as in the case of the ValorE software developed by Acutis et al. (2014). This software integrates GIS and DSS with the ability to manage complex data sets, perform spatial analysis and provide GIS maps of spatially explicit results describing phenomena where location is critical. AgriGigCAT, developed by Kamilaris et al. (2018), is software that blends geophysical data with spatial and big data analysis to estimate the impact of agricultural activities on soil, water, and air. Geospatial analysis are performed and visualized using ArcGIS. On the other hand, to control and limit the accumulation and biotransfer of HMs in the soil, Río et al. (2011) developed a DSS called FARMERS.

3.4.2.2. Water pollution. Four articles (Table S2) focus on N as a potential water pollution source, using interpolation methods to address its spatial distribution. In the context of nitrate pollution, He et al. (2019) combine the Inverse Distance Weighted (IDW) method with the Least Squares Surface Fitting (LSSF) model to assess the effect of aquifer intrinsic vulnerability and total soil nitrogen (TSN) on groundwater nitrate pollution (He et al., 2019; Netshiendeulu and Motebe, 2012). IDW is an easy-to-use and interpret interpolation method, but the disadvantage is that it is not based on a specific spatial correlation model (Hou et al., 2017). To determine the susceptibility of private wells to nitrate contamination, Hoppe et al. (2014) considered cropland, pasture and grassland as areas designated for the agronomic use of livestock manure and applied a buffer of 16 km around each Confined Animal Feeding Operation (CAFO), understood as the maximum transport distance of manure. Within this buffer area, the N estimates were distributed using the weighted distance technique, so that greater application was achieved on land close to the farm and reduced as distance increased, thus achieving nitrogen loading in these areas. Infascelli et al. (2009) on the other hand, in order to determine whether there is a negative or positive spatial correlation between the nitrogen load from buffalo or cattle farms in the province of Caserta and the nitrate level in groundwater, used the Kriging interpolation both thus assessing the distribution of nitrogen from livestock manure and predicting the nitrate concentration in unsampled groundwater in the study area.

Moreover, in the methodologies analysed for determining water pollution, further and different approaches were found (Fig. 6). In order to study nitrate pollution, machine learning algorithms have been developed. As demonstrated by Cardenas-Martinez et al. (2021), Random Forest (RF) is one of the most advantageous algorithms for predicting groundwater pollution caused by nitrates, suggesting that it can be improved by integrating with Feature-Selection (FS) techniques as well as by reducing the learning time.

Monitoring phosphorus pollution and its spatial distribution is crucial (Ngo et al., 2022). Indeed, Couto et al. (2018) investigated phosphorus pollution in a basin located in an area exposed to pig slurry application by developing an index from the estimated soil loss, the distance of the P source to the basin and the phosphorus content in the soil. Euclidean distance was used in GIS to generate the distance of the P source to the basin, which was classified into 5 classes and subjected to a multi-criteria evaluation. In order to mitigate phosphorus pollution in water bodies, Martín-Hernández et al. (2021) developed the COW2-NTRIENT (Cattle Organic Waste to NUTRIent and ENergy Technologies) decision support framework based on three models, one of which is GIS-based, to provide the location of livestock farms and assess their vulnerability to pollution using three indicators: Trophic State Index, Techno-ecological synergy metric and Soil phosphorus saturation.

In order to assess the potential environmental and economic impacts associated with pig farming, Pexas et al. (2021) integrated GIS into the LCA (Fig. 6) intending to evaluate the impact of different systems (Baseline practice, anaerobic digestion, slurry acidification and screw press separation) in different locations (4 case studies), taking into account the effect of spatial and topographical variability, considering two spatial parameters: the proximity of the farm to environmentally sensitive areas and the density of pigs at the municipal level. Spatial analysis was performed using QGIS, determining for each barycenter associated with a pig farm, manure application availability and estimated transport distance.

In some cases, GIS software is used in combination with models (Fig. 6) (Mouri and Aisaki, 2015). Guber et al. (2016) process the results of the SWAT model used to model the fate and transport of bacteria in catchments to perform spatial and temporal analyses of pathogen distribution in the watershed. Jiang et al. (2015) also proved that the SWAT model is appropriate for determining spatial and temporal patterns of NO_3^--N export and for identifying pollution hotspots. As well as Di Guardo and Finizio (2017) linked GIS with predictive models of veterinary medicinal products (VMPs) leaching, developing a Support Information System (SIS) that is effective in producing a map of groundwater vulnerability and solving the issue of spatial and temporal variability of the different phenomena involved in lixiviation processes. In addition to the models, Gassman et al. (2010) present an overview of the model components and applications that they have developed. Agricultural Policy Environmental eXtender (APEX) is a model that was built to simulate management approaches, cropping systems, and other land uses in a wide range of land management and agricultural landscapes, simulating impacts by farms and small watersheds. This work also demonstrates the creation of a combined modelling system between ArcGIS and WinAPEX, in which ArcGIS is used to process data on soil distribution and characteristics, landscape characteristics, topography, and land use, and ArcGIS additionally offers various visualisations of the results of interest. APEX is also used in conjunction with other programs, as demonstrated by Saleh et al. (2011), who combine it with Nutrient Tracking Tool (NTrT), a model that calculates N and P losses.

3.4.2.3. Air pollution. Most articles in this section focus on gaseous emissions modelling (mainly GHG and NH_3) and their spatiotemporal variation. Indeed, air pollution due to GHG and NH_3 emissions into the atmosphere is generally related to the livestock sector. Reliable emission inventories are required to comprehend the magnitude of these environmental issues. This is mainly due to the variability of the emission process and the difficulties in always obtaining reliable emission measurements. Furthermore, not only is the intensity of emissions essential but so is their location (Kuenen et al., 2014). These aspects are helpful to support the development of emissions reduction policies (Long et al., 2021). According to Long et al. (2021), the resolution of spatial emissions is important, suggesting that a 200 × 200 m grid, derived from landscape metrics and the information loss assessment model, provides optimal spatial resolution for CO_2 at the provincial scale.

Over the years, the creation of GHG and NH_3 emission maps from different sources was investigated: enteric fermentation (Chhabra et al., 2009), manure management (Wang et al., 2022) and synthetic and organic fertiliser application (Xu et al., 2015). These maps make it possible to visualize the distribution of the emissions of a specific area under study, using different emission estimating methods. Specifically, Chhabra et al. (2013) estimated greenhouse gas emissions, based on the use of coefficients from IPCC guidelines, and linked them to the GIS land coverage map, which was obtained through remote sensing (Fig. 6). For estimating and mapping N_2O and CH_4 emissions, Dimitrov and Wang (2019) developed the Geographic inventory Framework (GiF) tool. This consists of a series of Python programs connected to each other to maintain the integrity of the tool, a GIS component for the creation of maps and agricultural databases and finally a component for calculating emissions starting from the IPCC guidelines.

Estimating and forecasting GHG emissions from livestock production systems, considering the soil organic carbon (SOC) balance, is important for identifying optimal management practices (Jebari et al., 2023). A modelling framework including GIS, a Roth model to simulate SOC changes and IPCC Tier 2 methods to estimate emissions, based on characterising livestock, feeding and manure management, were used by Jebari et al. (2022).

Garnier et al. (2019) use the GRAFS approach to establish the GHG emissions budget, which takes consideration of four compartments (crop, pasture, livestock system, and local population) to describe the agricultural sector of a geographical area by studying N, P, C fluxes and integrating them with atmospheric losses. A suitable methodology was used to reconstruct N_2O, CH_4 and CO_2 emissions with their specific origin. For N_2O, an empirical connection was utilized to link N_2O emissions to fertilization, temperature, and precipitation. CH_4 emissions were calculated using livestock numbers and particular emission coefficients. Finally, a model based on CO_2 emissions from mechanical labour, livestock activities, and fertiliser production was utilized to calculate CO_2 emissions. Regarding NH_3 emissions, Ge et al. (2020) created an emission model with two components: a spatial allocator and a temporal allocator that focuses on NH_3 emissions from housing, storage, and manure application. The spatial allocator incorporates INTEGRATOR (Integrated Nitrogen Tool across Europe for Greenhouse gases and Ammonia Targeted to Operational Responses) agricultural emission data into MACC-III (Monitoring Atmospheric Composition and Climate-III). MACC-III is a European level inventory of NH_3 emissions based on annual emissions from the agricultural and non-agricultural sectors, with a resolution of 7 km × 7 km on latitude-longitude grids in the WG84 reference system. This differentiates emissions by animal type, but has the disadvantage of not categorizing the impact of various agricultural activities on emissions in more depth. As a result, it is supplemented by the N-cycle model (INTEGRATOR), which allows for the calculation of land system balances such as uptake, emissions, and losses. In this model, emissions are determined in NitroEurope classification Units (NCUs), which are made up of multiple 1 km × 1 km polygons in the ETRS89/LAEA Europe coordinate system. Successively, Ge et al. (2023) improved the emission model by using a high-resolution crop map, from Sentinel-2 data, and livestock farm information.

Leifer et al. (2018) combine mobile in situ data with satellite and airborne remote sensing platforms: i) AMOG Surveyor for in-situ detections of 13 gases at 5 and 3 m above ground; ii) MISTIR, a mobile spectrophotometer capable of determining column densities of gaseous components; iii) Mako for airborne spectroscopy data collection; and iv) satellite observations using the IASI spectrophotometer on board MetOp-B. The goal is to handle the spatial and temporal issues of substantial variation in emissions at various scales.

Eventually, another kind of application in this sub-area is assessing air quality in 3 schools in the vicinity of livestock farms, evaluating the relationship with the spatial distribution of farms, wind direction, and weather conditions (Guidry et al., 2017). This study considered hydrogen sulphide (H_2S), a toxic gas. To this end, a geodatabase containing information on the location of stables and lagoons was created, and 3 study areas were defined, each with a radius of 5 km and an area of 79 km^2. Within these areas, orthoimages were inspected in ArcGIS to identify stables and lagoons. Sampling periods were conducted for each school to monitor H_2S. In order to attain a low emissions system, a number of these publications offer insights into the spatial knowledge of emissions that can also be utilized in other subject areas. Finally, they have shown that more accurate and thorough model input data or comprehensive agricultural information is needed to produce a reliable result.

3.4.3. Landscape management/development

3.4.3.1. Land suitability studies for livestock manure management. Many works aimed at identifying suitable and available areas for agronomic management of livestock manure, focusing on spatial effects. Cervelli et al. (2021), developed maps with different degrees of suitability, by means of an S-MCDA process, supported by expert opinion, based on the selection of constraints and evaluation factors. A slightly different approach was taken by Saha et al. (2018) who used GIS to produce a map of four suitability classes, from less suitable to highly suitable areas, in southeastern Pennsylvania at a resolution of 30 m, based on a two-level suitability analysis. The first tier classified the available (suitable) and excluded (unsuitable) areas based on environmental vulnerability factors, including proximity to a watercourse, shallow soils or karst geology. Areas not subject to such vulnerability were assessed in the second-tier analysis, considering slope conditions, nutrient leaching and run-off potential as vulnerability factors. Nicholson et al. (2012) have developed a GIS-based tool, called ALOWACE, which can estimate the amount of N produced by farms and the availability of land for organic matter application, considering physical and legal constraints: land use data, exclusions and restrictions, topography, proximity to watercourses, Sites of Special Scientific Interest (SSSI), National Nature Reserves (NNR), Environmentally Sensitive Areas (ESA), Nitrate Vulnerable Zones, soil characteristics, material nitrogen loading, phosphorus loading and soil heavy metal concentrations. The clustering of CAFOs and the resulting use of manure lead to changes in land use and land use patterns. Miralha et al. (2021) compared areas affected by CAFOs, considering an impact area of a 15 km radius from each CAFO, with control areas, i.e. outside the radius considered. To quantify the extent and nature of the impacts, Moderate Resolution Imaging Spectrometer (MODIS) data were used to assess land use change from 2000 to 2018 in two states in the United States (U.S.). In addition, using a combination of longitudinal regression analysis and GIS, land use change is also examined to assess the relationship with water pollution (Rothenberger et al., 2009). Understanding the intensity and extent of application that may occur in unknown areas can support strategies to mitigate the negative impacts of this practice. Recent advances in remote sensing and machine learning can provide insights into livestock manure management. Shea et al. (2022), developed a machine-learning approach (Fig. 6) to identifying sprayed areas using ArcGIS for spatial analysis. In this study, satellite imagery and other land cover and land use data were collected to aid in the identification of sprayed and non-sprayed areas, including satellite imagery to measure soil and vegetation water content, vegetation delineation, and phenological crop cover and evapotranspiration data, as well as data on target crops, land cover and land use, soil water capacity, and estimated distance between spreading fields and lagoons. To distinguish between sprayed and unsprayed fields, they combined multiple observations from synthetic aperture radar, optical imagery obtained from Sentinel-2 for a better spatial resolution to generate the Normalised Difference Vegetation Index (NDVI) and Modified Normalised Difference Water Index (MNDWI), and thermal imagery to analyse changes in soil temperature. Christenson and Serre (2017) also used remote sensing data to identify crop type and quantify PAN_{bal}, which is the difference between the N applied and the N utilized by the crop, which, according to the regulations, must have a negative value, since a positive value indicates that not all the nitrogen applied is fully taken up by the crops. Knowing the crop in a field provides the different nutrient requirements of the crops. This work shows that remote sensing can make precision agriculture possible by providing an ideal tool for the implementation of nutrient management plans.

Suitable areas for spreading away from the farm represent a high cost to the farmer, so GIS models are being developed that integrate different aspects of spreading. Paudel et al. (2009) set out to develop optimal pathways, by looking at farm location, road network characteristics, land use and soil types, all of which influence livestock manure use. According to Paudel et al. (2009), soil types make it economically and environmentally advantageous to apply only to soils with good retention capacity, reducing leaching. Furthermore, some localities or communities have banned manure transport for environmental reasons, which may result in longer distances to reach the destination. GIS modelling allows the various factors involved to be considered and, through the development of the origin and destination (OD) cost matrix, generates actual routes and identifies those accessible to vehicles. In the event of restrictions, GIS modifies the route and uses stochastic methods to identify the most convenient route (Paudel et al., 2009). Tampio et al. (2017) used the ArcGIS Network Analyst (Fig. 6) OD cost matrix tool to derive the shortest distances for transporting digestate from the biogas plant to adjacent cropland, assuming that the fertiliser required by the crops would guarantee the digestate.

3.4.3.2. Spatial planning of animal housing and treatment plants. GIS spatial analysis has a potential use in evaluating the spatial distribution of livestock and poultry farms (LPFs), Yan et al. (2017b) developed a plan for the relocation of farms that should be relocated or closed due to their location. This plan was based on the spatial suitability assessed by environmental, economic and safety indices and the weighting of these indices using the AHP method, and on the estimation of the N load of livestock manure on agricultural land (Yan et al., 2017a). For farms in forbidden areas, relocation to neighbouring farmland with an N load of $<$40 kg/ha and high environmental suitability was recommended. Similarly, by integrating GIS with the Hasse diagram technique, Liu et al. (2022) assess the suitability of LPFs. Also, Sarr et al. (2010) in their work set themselves the objective of identifying suitable places and those to avoid for the installation of swine farms. They developed a structured model in two parts, the first identified the suitable areas through the intersection of the vegetation layer with areas with a slope $\leq$ 5 %, extracted from the DEM. The second part identified, however, those to be avoided by applying buffer zones around critical points (hydrography, roads and residences). For the residences, a 1300 m buffer was applied based on an air dispersion model to reduce the odour problem. Finally, the intersection of the two parts allowed identification with high security. Yan et al. (2021a) propose the relocation of pig production capacity to areas with greater environmental capacity and higher maize production, assessed through the definition of indices, i.e. the alert value of the equivalent manure load on land, the surplus or potential equivalent pigs and the Aggregated Advantage Index (AAI), combined with GIS software. Additionally, Yan et al. (2020) constructed a system known as the comprehensive comparative advantage index (CCAI) that was specifically designed to track the growth of pig farming. This system comprises a number of indices, such as resource endowment, livestock manure's N and P loading, agricultural area per capita, maize and soybean CCAI, rural employment, and average wages for farm workers.

This section also includes studies aimed at determining the appropriate location of storage facilities to reduce transport and P losses; Sharara et al. (2017) developed a decision support tool based on a mathematical formulation integrated with geospatial analysis and mapping software, where geo-referenced livestock data sets are a key component.

GIS mapping is also used to examine the economics of effluent management modifications, identifying short-term (related to spreading, transport, and treatment) and medium-term (associated with cropping system changes) costs (Mann and Grant, 2015). The cost-effectiveness of a given treatment that allows organic fertiliser production from livestock manure can be assessed using GIS approaches by evaluating the spatial availability of solid and liquid effluents in a specific area (Haase et al., 2017).

4. Needs, prospectives and conclusions

4.1. Bibliometric analysis

The review analysis concerning the research articles focused on manure management based on geographical analysis, revealed important aspects for both practical and scientific research as well as for policy makers. China and the United States produce the majority of the 139 publications, accounting for 37 % of the total. Three main macro application areas emerged, namely Bioenergy, Environmental pollution and Landscape management/development. The keywords "bioenergy" and "manure" play an important role in this inquiry. The results of the S-curve show that the topic is entering a phase of maturity, which can be seen as a pivot point for the new emergencies facing research. This means that the topic must turn to new approaches that take into account environmental, social and economic dimensions.

4.2. Focus area

Among treatments suitable for manure management, anaerobic digestion confirmed to be the most frequent topic in the focus area of Bioenergy due to the valorisation of livestock manure. From the landscape perspective, anaerobic digestion is often supported by a spatial analysis for optimal siting of plants. On the other hand, the investigation revealed a limited use of spatial analysis when nutrient recovery follows energy production. However, it could be of support for mitigating the impact of animal manure thanks to the rapid identification of cluster areas regarding nutrients content. Specifically, the network analysis can help properly estimate by-products as feedstock for biogas plants, overcoming one of the most challenging tasks plant feeding. GIS-based techniques for economic and environmental assessment are also important for reducing operational cost obstacles and improving adoption by farmers and the community. Research suggests that plants are increasingly being placed in strategic locations. The proper siting is also determined by the local geography, settlement patterns, and economics of the research areas. Consequently, the same technique or methodology applied in different study areas may provide different results. A proper result is also related to the analysis criteria chosen, as important criteria in one study area may differ from those in other study areas. As a result, a broader investigation is required, analysing diverse landscape structures or comparing very different places using the same approach. As well as the significance of analysing and comparing results from various multi-criteria analysis approaches, other factors to consider for the best location are the availability and suitability of agricultural land for the disposal of the digestate produced by the process. Spatial studies can also determine whether a location is suitable for animal farms and associated management practices without affecting environmental quality. We evaluated the use of spatial analysis to analyse the potential contamination and sensitivity of soils owing to the pollutants described in this research as a result of manure application to the soil. This research uncovered the key components of these techniques, which were frequently related to the correct and representative sampling of the study area. Moreover, as this information is sometimes absent or hard to locate in animal databases, the simulation of manure distribution to the soil is frequently predicated on an estimated range from the farm production centre. As a result, the actual problem may be overestimated or underestimated. However, as studies frequently demonstrate a non-exhaustive study, a more thorough investigation of potential sources or sources of contamination is required. Examples of such sources include various kinds of livestock manure or other sources (synthetic fertilizers, chemicals, etc.). GHG and NH_3 emissions from livestock farming are expected to become an increasingly important problem, and research has demonstrated that the spatial method used in this area can aid in better understanding spatial patterns. The analysis of focus areas showed that only 15 % of the articles fell under *landscape management/development*. Due to the importance of effective planning, the ability to monitor and reduce risks, and active community participation are all critical components in preventing difficulties. In particular, the new policies aim to reduce the impact of the livestock sector at the territorial level, focusing mainly on environmental sustainability and reducing greenhouse gas and ammonia emissions. Finally, the presented review demonstrates the utility of spatial analysis techniques in the growing importance of precision agriculture.

4.3. Limitations and prospects for further investigation of the techniques

The use of literature analysis to study the development of academic research and the study of applications of GIS analysis simultaneously provides insight into the most common application areas and the most interesting approaches. This review paper analysed in depth the different technical aspects of the reviewed papers in order to enable future researchers to identify applicable approaches in the areas of study of their interest and to identify promising or expandable approaches for the sustainable development of the livestock sector. Since the literature review was limited to the *Scopus* scientific literature dataset, some works indexed in other datasets (such as *Web of Science*) may not have been included in this work. From the observation of the results, the following considerations can be made: i) the siting of treatment plants by spatial analysis often does not take into account the land's capacity to receive the digestate produced without contributing excess nitrogen, economic analyses and political and regulatory aspects that can greatly alter the result; ii) multi-criteria analysis work requires comparisons to be made using different multi-criteria analyses, which may give different results; iii) spatial analysis work needs to be extended to consider greenhouse gas and ammonia emissions; iv) few papers consider spatio-temporal analysis.

Future research directions can be derived from these findings:

- Compare several multi-criteria analyses carried out on the same research area;
- Take into account political and regulatory factors when analysing the location of treatment plants;
- Extending and improving emissions-related geographical analysis;

- Time series data should be integrated into GIS studies to better understand the impact of livestock production on land, water, and air.

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CRediT authorship contribution statement

Raffaele Grieco: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Elena Cervelli:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Marco Bovo:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Stefania Pindozzi:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Ester Scotto di Perta:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Patrizia Tassinari:** Writing – review & editing, Methodology, Funding acquisition, Data curation, Conceptualization. **Daniele Torreggiani:** Writing – review & editing, Methodology, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

No new data were created in this study. Data sharing is not applicable to this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176687.

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