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Research Trends on Nutrient Management From Digestates Assessed Using a Bibliometric Approach

*Albert Magrí**

Department of Agri-Food Engineering and Biotechnology, Universitat Politècnica de Catalunya, Castelldefels, Spain

Anaerobic digestion is often applied for biological conversion and valorization of organic waste, waste water and other biomass sources as renewable energy and biofuel in the form of biomethane. Composition of the material remaining after digestion, or digestate, is highly dependent on processed feedstocks. This by-product is usually rich in nutrients such as nitrogen and phosphorus, so it is potentially reusable as fertilizer or nutritive broth in agricultural systems. Alternatively, the digestate may need post-treatment based on nutrient removal or recovery strategies. The use of life-cycle assessment tools is becoming popular to analyze nutrient handling scenarios. This study reviews, through a bibliometric-based approach, the research outputs and global trends in the area of knowledge of nutrient management from digestates in the last 30 years, 2017 included. Documentary production followed an upward trend, with a relative productivity in the last 3 years greater than 37% of the total number of appeared publications. China, USA and Spain were the three most prolific countries. The particular interest in nutrient management alternatives and its evolution were identified. Trends for promoting sustainability include low environmental impact, holistic agro-energy solutions, reduced consumption of resources during digestate processing, and circular economy scenarios based on concepts such as (bio)refinery and recovery of valuable and marketable products.

Keywords: biogas digester effluent, nitrogen, phosphorus, soil application, treatment, nutrient removal, nutrient recovery, life-cycle assessment

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Correspondence:
Albert Magrí
albert.magri@upc.edu;
albert.magri@gmail.com

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INTRODUCTION

Anaerobic digestion (AD) is an environmental biotechnology which is increasingly applied for the energetic valorization of organic waste(water) streams and other biomass sources (Appels et al., 2011; Wang et al., 2013). Owing to this technology meet targets such as production of renewable energy and mitigation of climate change, it helps fostering transition from dependence on fossil fuels to other more sustainable energy-producing scenarios. Positive energy balance, stabilization of organic matter, potential for inactivating pathogenic microorganisms, reduction of sludge handling requirements, robustness of the process, and mitigation of greenhouse gas (GHG) emissions are some of the factors that explain current attention to this technology. Resulting products from the AD process are biogas and digestate.

The biogas which is formed in AD (60–70% vol. of methane, CH_4) has a high calorific value, and it can be used for the generation of heat and electricity. Additionally, if upgraded to biomethane, then it can be injected into the natural gas grid or used as transportation fuel (Pöschl et al., 2010). Co-digestion based on blending different raw organic materials from agricultural, industrial, or urban sources is frequently applied to boost biogas production (Mata-Alvarez et al., 2014). In addition, there is a growing concern in upgrading conventional operative energy-consuming wastewater treatment plants (WWTPs), which mostly depend on the aerobic biodegradation of the organic carbon (C), by moving towards anaerobic technologies, including AD, that may allow energy neutrality, or even net energy recovery (Scherson and Criddle, 2014).

The neologism "digestate" is increasingly used to refer to the digested effluent produced in anaerobic digesters (Magrí et al., 2017). Composition and quality of this by-product is strongly dependent on the processed feedstocks and applied treatment conditions (Makádi et al., 2012; Fuchs and Drosg, 2013). Thus, to assure that quality and safety are preserved, presence in digestate of undesired materials and pollutants of physical, chemical or biological nature must be prevented. Digestate produced using agricultural, agro-industrial and food processing feedstocks is usually a high-quality product which can be used advantageously as fertilizer. A robust and stable AD process has a positive impact on the quality of the digestate because, in some measure, is capable to degrade many of the undesired compounds and contaminants eventually supplied with the feedstock (Al Seadi and Lukehurst, 2012). The dry matter content will determine handling of the digestate as a solid or as a liquid stream. The total nitrogen (N) and phosphorus (P) contents are not affected by the digestion process although it favors their mineralization (Mehta and Batstone, 2013).

Typical challenges for waste management in agroecosystems are the improvement on nutrient availability in soil cycling; the development of technologies for nutrient reuse; the mitigation of contaminants and improvement of food safety; the mitigation of environmental emissions; and the enhancement of soil health and function (Bernal, 2017). The implementation of sustainable agro-energy systems integrating bioenergy and crops production is also attracting increasing attention (Siegmeier et al., 2015). Digestate application to agricultural soils as a nutrient source according to local regulations is interesting (Makádi et al., 2012; Möller and Müller, 2012; Nkoa, 2014) from both the economic and environmental perspectives owing to the implicit replacement of mineral fertilizers. However, factors such as transport needs, water content, and presence of heavy metals, organic micropollutants or pathogens may hinder this handling strategy (Ghafoori and Flynn, 2007; Nkoa, 2014). Beyond soil application, therefore, additional treatment of the digestate may be required to improve the capability of transporting valuable constituents, to protect human health and to prevent negative impacts on the receiving agricultural ecosystems, water bodies and atmosphere (Sheets et al., 2015). Storage, land application or post-treatment under inappropriate conditions may lead to nutrient leaching and runoff (Zhu et al., 2009) as well as gaseous N emission as ammonia (NH_3) and nitrous oxide (N_2O)—the latter being a powerful GHG (Amon et al., 2006; Massara et al., 2017).

Solid-liquid separation of the digestates is frequently implemented and provides two different mass fractions that can be handled independently (Fuchs and Drosg, 2013; Tambone et al., 2017). The solid fraction -which usually contains a large amount of fibers and P- can be transported longer distances in order to be used as slow release fertilizer owing to the diminution in the water content, or undergo further treatment (e.g., composting, drying, etc.) to produce added-value products (Rehl and Müller, 2011; Sheets et al., 2015). Otherwise, the liquid fraction -also named reject water, supernatant, or centrate, among other names, depending on the context and separation technology applied, and which usually contains the larger part of N and potassium- can be used for the fertigation of nearby arable land, or post-processed in accordance with its typical low C:N ratio applying nutrient removal or nutrient recovery alternatives (Malamis et al., 2014; Mehta et al., 2015; Monlau et al., 2015; Sheets et al., 2015; Vaneeckhaute et al., 2017; Monfet et al., 2018). N-removal involves the conversion of ammonium (NH_4^+) to nitrogen gas (N_2), an innocuous gas which is released to the atmosphere. Mostly, this group encompasses biological treatments including both conventional strategies based on nitrification-heterotrophic denitrification (NDN) and advanced strategies such as partial nitritation-anaerobic ammonium oxidation (PN-anammox) (Malamis et al., 2014). Recovery consists on producing new material flows which subsequently can be reused -e.g., as agricultural fertilizer or nutrient broth-. Concentration by vacuum evaporation, NH_3 stripping and absorption, biological accumulation by prokaryotic organisms and algae, membrane filtration, and phosphate precipitation (e.g., as struvite) are some particular processes that belong to this group (Mehta et al., 2015; Vaneeckhaute et al., 2017). The latter approach enables closing the nutrient cycle, which sounds always attractive in relation to sustainability. Nonetheless, other aspects like influent strength, resource consumption, process efficiency, environmental impact, local market prices, current legislation and national policies must be regarded to assess the final feasibility of these technologies (Rehl and Müller, 2011; Magrí et al., 2013; Rodriguez-Garcia et al., 2014; Batstone et al., 2015).

In many disciplines of science and engineering, research outputs generated by researchers and scholars worldwide are mostly disseminated by publishing papers in specialized journals. The impact of these publications into the research community is frequently assessed through bibliometric analysis. This method also enables the quantitative review of scientific productivity and the identification of trends on research (Moed et al., 2005). Bibliometrics has been applied in particular in the field of environmental science and engineering. This is the case, for instance, in topics such as AD (Wang et al., 2013), solid waste (Yang et al., 2013), upflow anaerobic sludge blanket -UASB- technology (Zhang et al., 2014), life-cycle assessment (Hou et al., 2015), ammonia oxidation (Zheng et al., 2017a), and nutrient management from digestates (Magrí et al., 2017), among others. The mapping of tendencies at the intersection of two research topics has also been considered; e.g., algae and bioenergy (Konur, 2011), organic farming and bioenergy (Siegmeier and Möller, 2013), or wastewater and energy (Zheng et al., 2017b).

As an update of the work published by Magrí et al. (2017), the author addresses the bibliometric assessment of the scientific development and global trends in nutrient (N and P) management from digestates during the last three decades. Thus, the above referred study, originally focused on the joint analysis of publications and patents, has been revised. The new analysis is exclusively focused on publications, the multi-term topic search is enhanced, the time span is extended from 20 years (from 1995 to 2014) to 30 years (from 1988 to 2017), and new review comments are finally provided.

METHODS

Data Source

Publications were joined on-line via the Science Citation Index Expanded (SCIE) accessed through the Web of Science Core Collection -Clarivate Analytics, United States of America (USA)-. This is the most frequently used database for the analysis of scientific publications in journals. In 2016, SCIE indexed 8,879 journals across 177 subject categories. The time span considered for this study was the last three decades, from 1988 to 2017 included (retrieved data was updated on February 1st, 2018). The search was carried out within the fields: *title*, *abstract*, *author-provided keywords*, and *keywords plus*. Nonetheless, on some occasions, particularly for the publications appeared before 1990, such fields in the database are partly empty. This fact may have limited the number of publications finally retrieved in those early years. Search for publications was conducted after revision of the multi-term topic search (TS) used by Magrí et al. (2017):

$$TS = TS1 \text{ AND } TS2$$

where TS1 aims to identify the by-product on which the study is focused. It contains different terms that may be used to mention such by-product; i.e., short name (e.g., digestate, biogas residue, reject water, etc.), or a descriptive explanation by linking several words describing the process, or site of production, and the material treated (e.g., anaerobically treated manure, biogas digester effluent, etc.),

TS1 = [“*digestate*” OR “reject* *water*” OR “biogas effluent*” OR “biogas residue*” OR “biogas slurr*” OR “anaerobic liquor*” OR “anaerobic supernatant*” OR (((“digestion” NEAR/3 (“anaerobic” OR “biogas” OR “*methane”)) OR “digested” OR “*digester*” OR “*digestor*” OR (((“treat*” OR “*reactor*”) NEAR/3 “anaerobic*”) AND (“biogas” OR “*methane” OR “*fuel*”))) AND ((“digestion” OR “digested” OR “*digester*” OR “*digestor*” OR “treat*” OR “*reactor*”) NEAR/3 (“*waste*” OR “*water*” OR “sludge*” OR “manure*” OR “dung*” OR “effluent*” OR “*slurr*” OR “residu*” OR “biosolid*” OR “leachate*” OR “supernatant*” OR “liquor*” OR “*stream*” OR “centrate*”)))]

whereas TS2 aims to identify the nutrients (e.g., nitrogen, phosphorus, etc.) to be handled and other fertilization-related topics.

TS2 = [“nitrogen*” OR “ammoni*” OR “phosph*” OR “nutrient*” OR “ferti*” OR “soil*” OR “land”].

Different authors may refer to the same concept using different terms, and chaining multiple words. In addition, the wide spectrum of this field of research, including many management and treatment alternatives, not only applying to digestates, hindered the definition of a simpler TS.

Refined Data

Only documents reported as articles were selected for conducting this study; reviews, meeting abstracts, notes, book chapters and other types of publications were discarded. Documents simultaneously indexed as articles and proceedings papers were, thus, accepted. The list of pre-selected articles included 5,677 items (93.6% of the total number of retrieved publications). The main indexed contents of these articles were saved to a Microsoft Excel file. Subsequently, such list was refined manually. Only those items that fitted the main goal were kept. Such screening consisted in reading the title and when needed, the abstract, to confirm the selection of each article. This resulted in a total of 2,314 articles (40.8% of the original number of articles), which have been cited 40,157 times and have reached an *h*-index of 82 by the end of the year 2017. Thus, the refining process was essential owing to the heterogeneity in the scope of the automatically retrieved articles, and although it is time-consuming, requires specific criteria and can introduce some subjectivity. The subsequent analysis of the retained articles was useful for quantifying annual productivity, as well as for identifying dominant SCIE subject categories and indexed journals, most productive countries, and relative interest in certain research topics and their development. The contribution of a country to an article was considered by the affiliation of at least one author. Articles published by authors from England, Scotland, Northern Ireland and Wales were grouped under the United Kingdom (UK). Articles published by authors from Hong Kong were grouped under China. Results of the analysis are presented graphically or in tables, and they are referred to the whole study period (1988–2017) and to ten 3-year partial periods, which allow smoothing yearly fluctuations.

RESULTS

Number of Published Articles

In the first 15-year period analyzed in this study (from 1988 to 2002), the number of published articles per year was low and did not experience significant changes, with record counts ranging from 0 to 32 (**Figure 1**). Thus, in the 90s, published articles averaged 16 items per year. Yet, in the next years, the publication rate raised sharply from 38 articles in 2003 up to a maximum of 313 articles in 2017. In order to compare the evolution of the annual number of published articles dealing with nutrient management from digestates with the overall number of

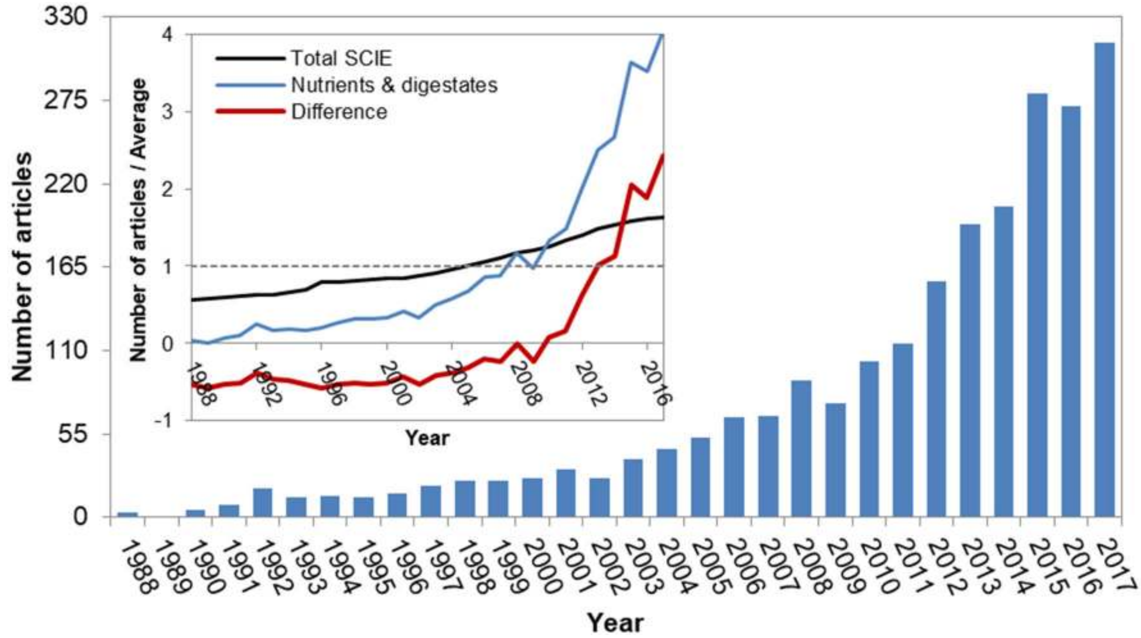

FIGURE 1 | Yearly number of published articles concerning nutrient management from digestates in the period 1988–2017.

articles indexed in SCIE, both time series were standardized by dividing the corresponding number of articles and the 30-year average (**Figure 1**). This analysis shown that, in recent years, the rising trend in the annual number of published papers focused on nutrient management from digestates has been more significant than in the overall number of articles, particularly after 2010. In relative terms, articles published in the last three years (from 2015 to 2017) accounted for 37.3% of the total documentary production.

Subject Categories and Scientific Journals

In the whole study period, articles dealing with nutrient management from digestates fell into 58 different SCIE subject categories, and were published in 351 indexed journals. The 10 most frequent categories are shown in **Figure 2**. The dominant category was "Environmental Sciences" with 1,105 articles (47.8%), followed by "Engineering, Environmental" and "Water Resources" with 717 (31.0%) and 478 (20.7%) articles, respectively. The categories "Engineering, Chemical" (50.2%) and "Environmental Sciences" (37.1%) were dominant in the most recent 3-year period relative to the total number of articles appeared in the period 1988–2017.

The 10 dominant journals are shown in **Figure 3**. Such journals published a total of 897 papers, which is 38.8% of the analyzed items. *Water Science and Technology* included the most with 251 articles (10.8%), subsequently followed by *Bioresource Technology* and *Water Research* with 209 (9.0%) and 92 (4.0%) articles, respectively. Seven of the top 10 journals are currently published by Elsevier. *Water Science and Technology* was also the most prolific journal in the early years with 32 articles published from 1988 to 1997 (28.6% of the total number of articles appeared in that decade). The journals *Science of the Total Environment* (81.1%) and *Journal of Cleaner Production* (71.1%) published the most number of articles in the last 3-year period relative to the total number of publications in the full period analyzed. In view of the results, only 48 journals (13.7%) published 10 or more articles in the topic under analysis from 1988 to 2017.

Productivity by Country

Authors with affiliation in 84 different countries contributed to the publication of articles dealing with nutrient management from digestates. The 10 most prolific countries were six in Europe, two in North America and two in Asia (**Figure 4**). Documentary production of such countries accounted for 69.5% of the total number of articles. China was the most productive country with 340 articles (14.7%), followed by USA (330 articles, 14.3%) and Spain (218 articles, 9.4%). The USA was the most prolific country in the early years (27 articles during 1988–1997; 24.1% of the total number of articles appeared in that decade). On the other hand, China (54.4%) and Italy (49.7%) published the most articles in the last 3-year period relative to the total number of publications in the full period analyzed. The most productive institutions regarding the total number of articles were mainly European. The list of institutions was headed by Ghent University in Belgium (50 articles), the Swedish University of Agricultural Sciences (45 articles) and Aarhus University in Denmark (44 articles). The first non-European institution was China Agricultural University which ranked 5th (37 articles).

Research Topics and Trends

Articles selected for conducting this study were analyzed to identify main research topics and associated trends. **Figure 5A**

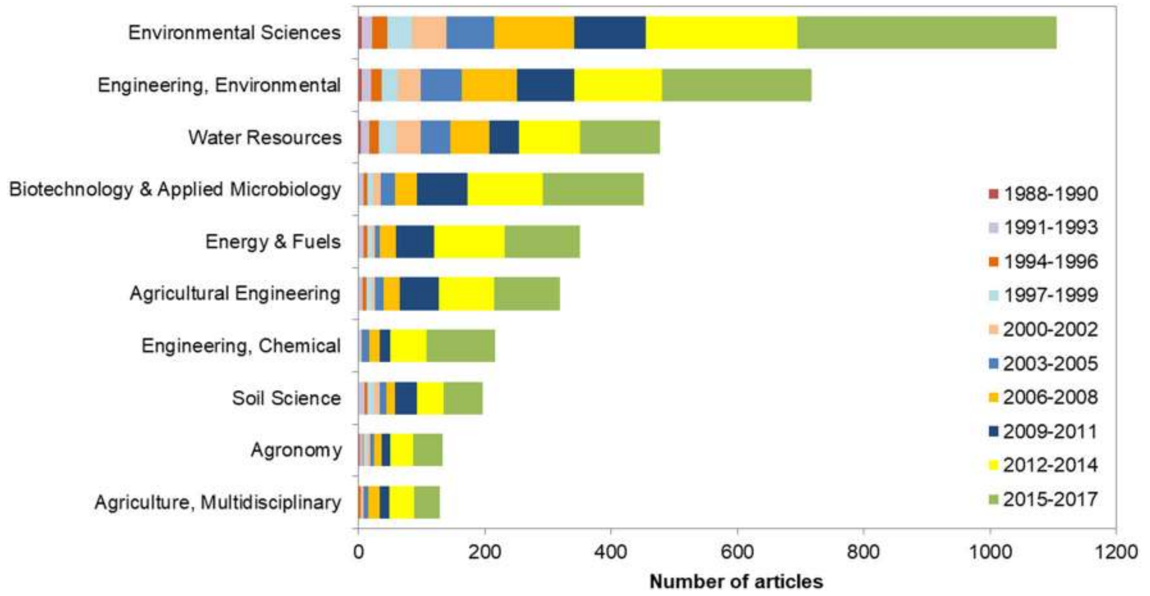

FIGURE 2 | Top 10 dominant SCIE subject categories based on the number of published articles concerning nutrient management from digestates in the period 1988–2017.

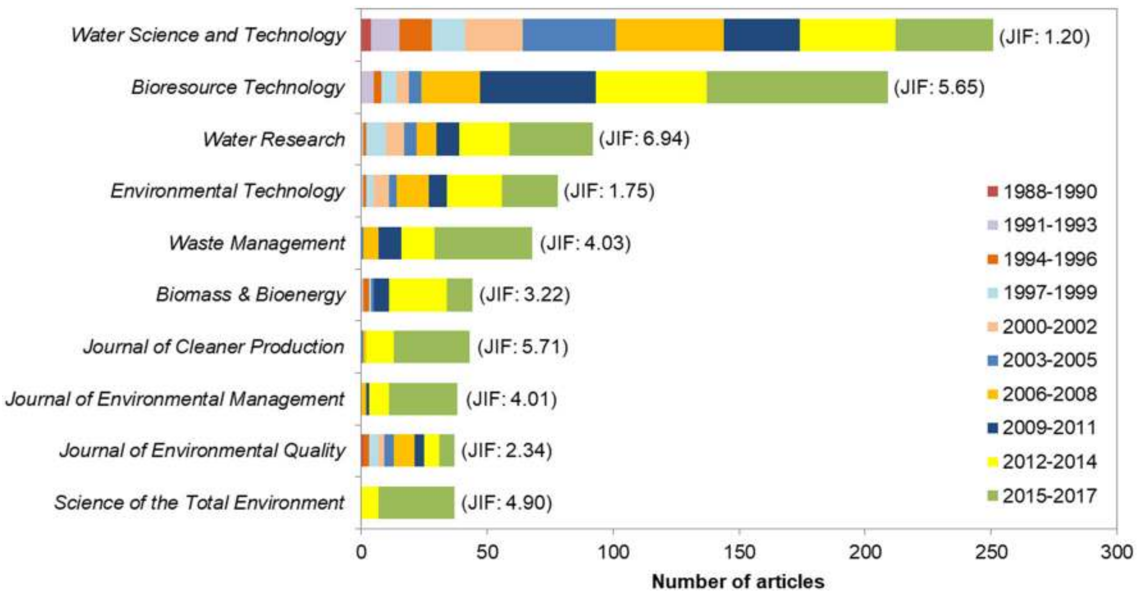

FIGURE 3 | Top 10 dominant journals based on the number of published articles concerning nutrient management from digestates in the period 1988–2017. JIF, Journal Impact Factor (year 2016).

shows the number of items focused on the management of a given nutrient (N and P) according to the publication fields *title* and *author-provided keywords*. Supposedly, such fields contain the most significant information that the authors want to convey the readers, as well as show tendencies in research activity (Li et al., 2009). In **Figure 5A**, "nutrients" refers to unspecific mentions, "nitrogen" includes specific mentions to the chemical element N and other related compounds (e.g., ammonium, ammonia, struvite, nitrous oxide, nitrite, and nitrate), and "phosphorus" includes specific mentions to the chemical element P and other related compounds (e.g., phosphate, apatite, and struvite). In all cases, there is an increasing trend regarding the number of articles, although "nitrogen" has clearly aroused the greatest interest. Recently, general references to "nutrients" have become more frequent than particular references to "phosphorus." On the other hand, **Figure 5B** shows the number of publications

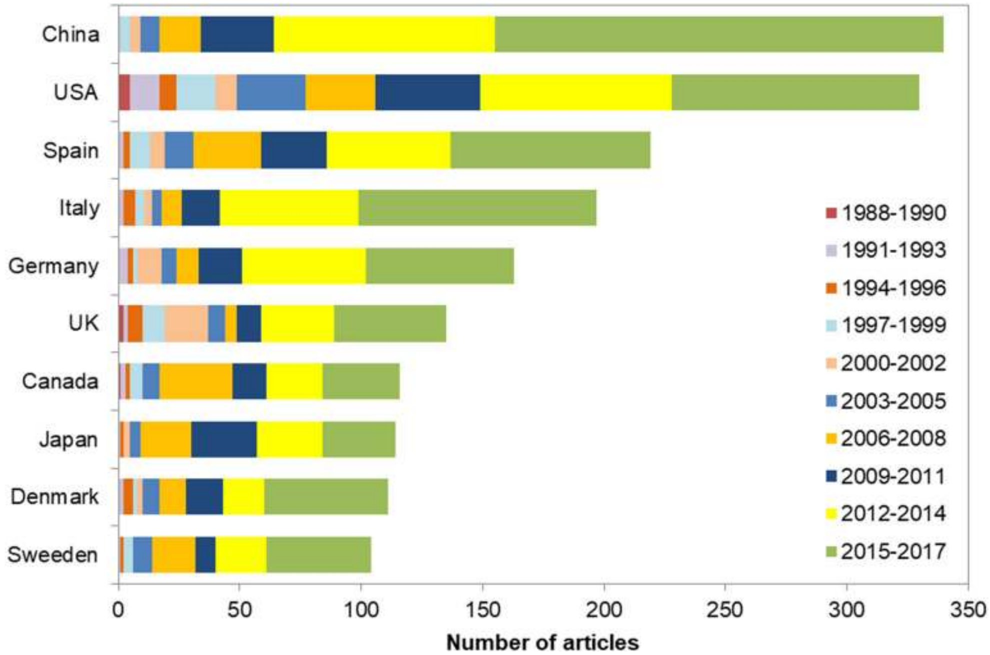

FIGURE 4 | Top 10 most productive countries based on the number of published articles concerning nutrient management from digestates in the period 1988–2017.

dealing with main research topics such as "crop nutrition & fertilization," "nutrient removal technologies," "nutrient recovery technologies," "gaseous emissions," and "environmental & life-cycle assessment". The lack of standardization in language may hinder this analysis since some terms are used vaguely; i.e., different authors use the same word to express different things, or use either synonyms or different terminology to define the same concept. Overall, research outputs were mostly linked to "crop nutrition & fertilization," as well as to the characterization of "nutrient recovery technologies." Despite the number of published articles dealing with "nutrient removal technologies" start growing significantly in the period 2003–2005, its trend was clearly surpassed in recent years by that of the "nutrient recovery technologies." Additionally, conceptual studies, addressing "environmental & life-cycle assessment," are attracting increasing attention since the period 2003–2005. In fact, both research topics "nutrient recovery technologies" and "environmental & life-cycle assessment" held the highest grow in the last three years relative to the total number of articles in the whole period (47%).

Particular trends in research of technologies targeting nutrient removal and nutrient recovery from digestates were also assessed (**Figure 6**). Removal related topics are shown in **Figure 6A**, where "nitrification" appears as the most frequent addressed issue. Research on "anammox" was found to start later than research on "heterotrophic denitrification," but then the first grew faster, particularly in the period 2006–2011. The number of articles appeared in the subsequent years was similar for both N-removal strategies. Research addressed on biological P-removal was much lower. On the other hand, recovery related topics are shown in **Figure 6B**. Albeit the highest number of published articles was attained by the topics "algae cultivation" and "phosphate precipitation," the corresponding publication patterns were significantly different. Thus, while the number of articles focused on the precipitation of phosphates increased quite steadily in the whole study period, the appearance of articles focused on the cultivation of algae raised sharply in the last years.

Finally, a citation impact assessment was performed. This analysis considered all articles, and also partial groups of articles, in accordance with the research topic and time interval (**Table 1**). The main topics taken into account were the same that those already identified in **Figure 5B**; this is "crop nutrition & fertilization," "nutrient removal technologies" (in particular those based on "heterotrophic denitrification" and "anammox"), "nutrient recovery technologies" (in particular those based on "algae cultivation," "(vermi)composting," "membrane filtration," and "phosphate precipitation"), "gaseous emissions," and "environmental & life-cycle assessment." The citation rate concerns the average number of cites per article and per year. Citations were grouped in 2-year periods after publication. The global citation rate (i.e., concerning all articles) averaged 2.63 whereas the particular citation rates (i.e., concerning all topics and time periods) ranged from 0.00 to 7.25. The sub-topic "anammox" gathered the highest citation rate for the whole study period (4.55), followed by "environmental & life-cycle assessment" (4.34) and "algae cultivation" (4.24).

None of the 10-top articles date back earlier than 1997 nor later than 2014. These articles have been highly cited, averaging from 14.4 to 79.3 times per year (the total number of cites received per article from the year of publication to the end of 2017

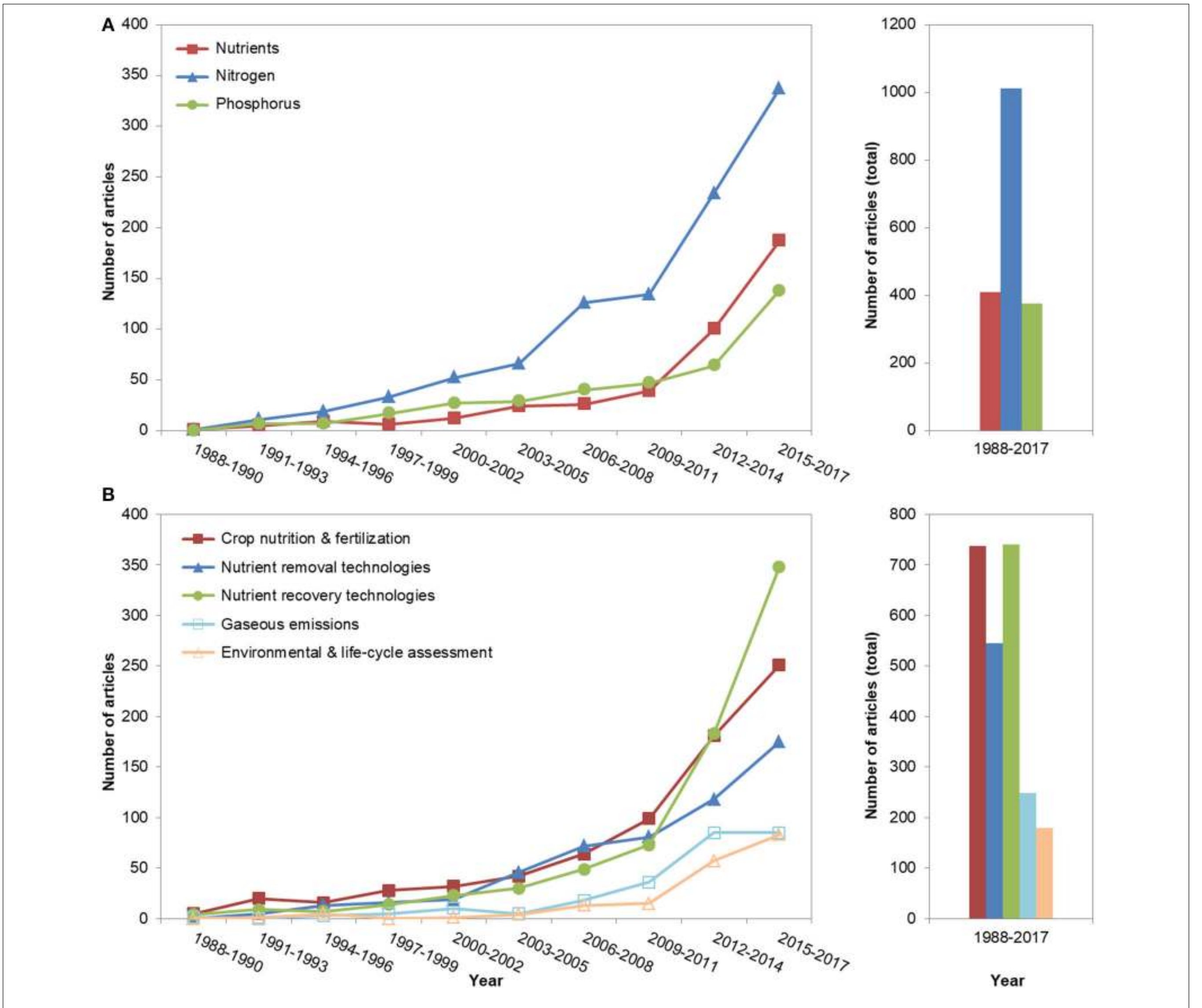

FIGURE 5 | Number of published articles concerning nutrient management from digestates in the period 1988–2017 grouped in 3-year partial periods. **(A)** Trends for assessed nutrients. **(B)** Trends for main research topics.

was from 235 to 469). Five of these articles appeared in the journal *Water Research*, and eight were authored by individuals with affiliation in European institutions. Even though the research topics of these top articles differed, N-removal applying the anammox process was the most recurrent topic (not less than five articles) with 3,185 cites in total (53.2% of the total number of cites counted).

DISCUSSION

The advance of knowledge in the field of nutrient management from digestates has been analyzed using bibliometric tools. A growing interest in this research topic -as main subject or sharing protagonism with the application of the AD process for producing renewable energy and biofuel in the form of biomethane- was confirmed in terms of annual number of published articles. Thus, 37% of the articles considered in this study appeared in the last three years. Such upward trend in written productivity was also pointed out by Wang et al. (2013) in a bibliometric study concerning research on AD for methane production. As likely reasons for the growing interest in AD, these authors referred to the emergence of a fossil energy crisis, the rise in the price of energy, and the general enhancement of social awareness, among others. Current energy policies are another factor leading in this direction by promoting the use of renewable resources for the production of biofuels. China, USA and Spain were identified as the three countries with higher numbers in published articles addressing nutrient management from digestates. A fast growing rate was particularly spotted for China in recent years -54.4% of the articles were published in

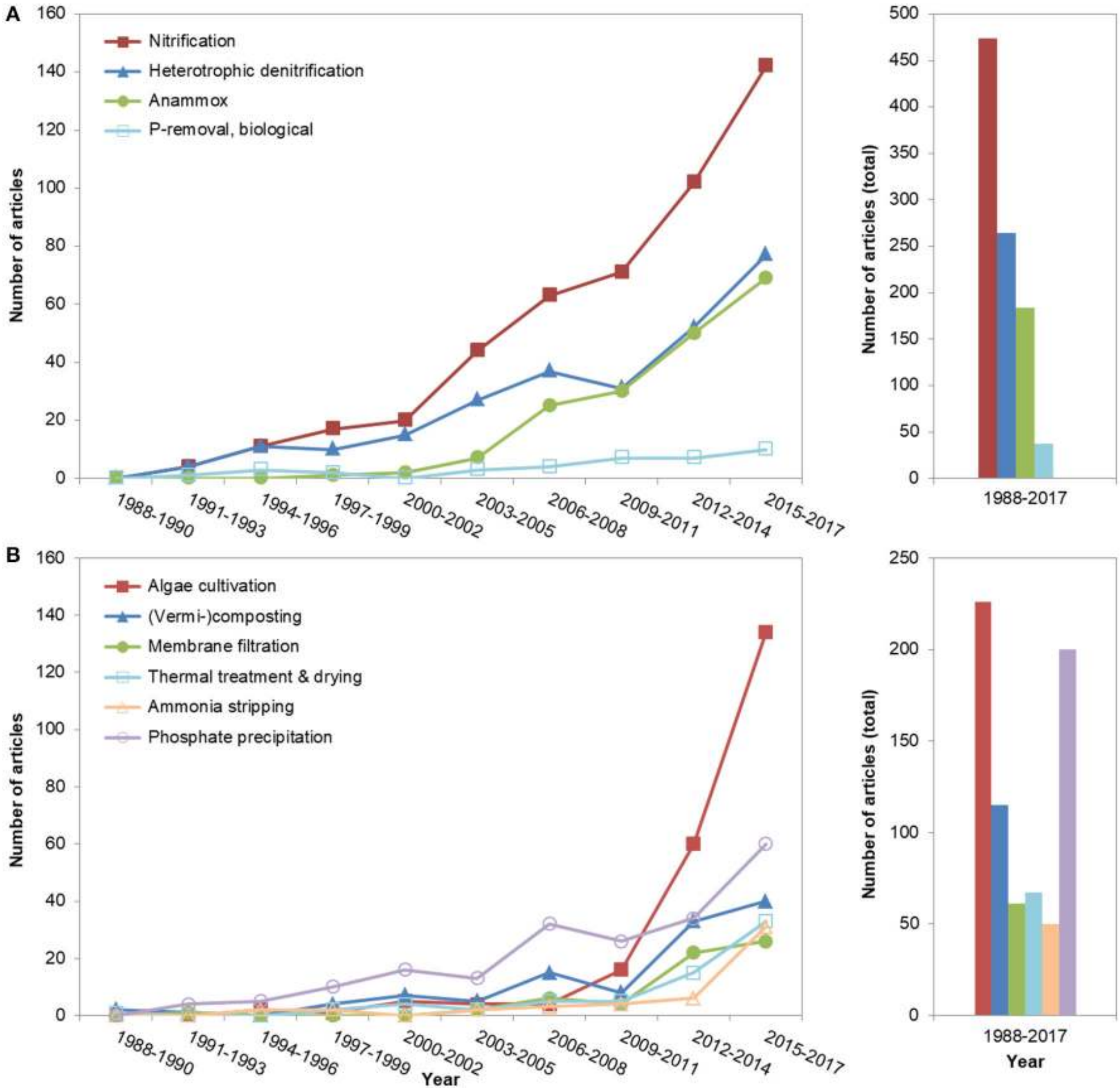

FIGURE 6 | Number of published articles concerning nutrient management from digestates in the period 1988–2017 grouped in 3-year partial periods. **(A)** Trends for technologies aiming to nutrient removal. **(B)** Trends for technologies aiming to nutrient recovery.

the last three years-, similarly as it has already been reported in other fields of chemical engineering (Fu et al., 2014). However, the most active institutions, and also the most cited articles, were still primarily European. Spain occupied the third position of the productivity ranking by country. Such good position may result quite surprising since Spain is not even member of the G7, and has lower population, gross domestic product, and renewable energy and environmental policies development, than other countries. In Europe, other countries such as Germany, UK or Italy produce larger amounts of biogas than Spain, and currently, primary energy production from biogas in this country is not growing. Accordingly, its ranking as European biogas producer has dropped from 7th in 2011 to 10th in 2016 (EurObserv'ER, 2012, 2017). The high rating for Spain regarding publication of scientific articles in nutrient management from digestates was already identified by Magrí et al. (2017). Nonetheless, the important increase in the number of published articles for the last years may involve fast changes in the rankings; e.g. China -which ranked 3rd in 2014 according to Magrí et al. (2017)- bypassed USA as the most productive country in only 3 years.

The reuse of digestate as fertilizer or soil improver has generated increasing scientific interest in the past decades (Hons et al., 1993; Möller and Müller, 2012; Nkoa, 2014). Questions regarding the effect of digestate application on nutrient mineralization, nutrient uptake, plant growth, phytotoxicity, and possible water pollution according to the land use, kind of soil, and loading rate have frequently been addressed (738 items in **Figure 5B**, accounting for 32% of the total number of articles). Other studies have focused on the monitoring

TABLE 1 | Citation rates for published articles concerning nutrient management from digestates in the period 1988–2017.

Research topic[a]	Full period[b,c]	Partial periods									
	1988–2017	1988–1990	1991–1993	1994–1996	1997–1999	2000–2002	2003–2005	2006–2008	2009–2011	2012–2014	2015–2017
All articles	2.63	1.00	0.72	0.85	1.01	1.26	1.49	1.95	2.84	3.35	3.49
Crop nutrition & fertilization	1.87	0.90	0.60	1.28	0.80	0.73	1.13	1.63	2.02	2.42	2.41
Nutrient removal technologies	2.75	0.00	1.10	0.73	1.19	1.97	1.60	2.26	3.48	3.42	3.13
- Heterotrophic denitrification	1.99	0.00	0.75	1.05	0.90	1.50	1.41	1.58	1.69	3.13	2.59
- Anammox	4.55	0.00	0.00	0.00	7.00	7.25	2.50	3.94	4.88	5.28	3.66
Nutrient recovery technologies	3.16	1.13	0.72	0.79	1.00	1.54	1.35	1.78	3.43	3.83	3.96
- Algae cultivation	4.24	0.00	0.00	0.50	0.00	0.80	2.13	2.38	4.88	4.82	4.25
- (Vermi)composting	2.33	0.50	1.00	0.00	1.00	0.57	2.50	1.77	3.63	3.06	2.03
- Membrane filtration	3.26	0.00	0.00	0.00	0.00	0.00	1.25	1.58	1.88	5.02	2.20
- Phosphate precipitation	2.25	0.00	1.38	1.30	1.55	1.88	1.85	1.44	2.67	2.94	3.57
Gaseous emissions	3.32	0.50	0.00	1.00	1.70	0.70	2.80	3.56	4.15	3.63	2.76
Environmental & life-cycle assessment	4.34	0.00	0.00	0.20	0.00	0.50	2.00	2.23	4.53	4.73	5.65

Results were grouped in 3-year partial periods as in ***Figures 5, 6***.

[a]*Research topics taken into account were: (i) "crop nutrition & fertilization" (including experimental developments concerning digestate characterization, soil amendment, agricultural fertilization, etc.), (ii) "nutrient removal technologies" (based on "heterotrophic denitrification"; "anammox"; etc.), (iii) "nutrient recovery technologies" (based on "algae cultivation"; "(vermi)composting"; "membrane filtration"; "phosphate precipitation"; etc.), (iv) "gaseous emissions"; and (v) "environmental & life-cycle assessment".*

[b]*Values correspond to average number of cites per article and per year taking into account the 2 years following publication (the publication year is not considered). Those articles published after 2015 were not included in calculations.*

[c]*Average number of total citations per article in the full period 1988–2017 (equivalent to cites per article after publication), if reading the research topics in descending order, were 17.4 (all articles), 14.2, 20.6, 15.8, 29.9 (anammox), 16.5, 14.9, 15.3, 16.7, 21.5, 22.1, and 18.9 (environmental & life-cycle assessment).*

of potential environmental impacts such as the emission of GHGs (i.e., CO_2, CH_4, and N_2O) and other atmospheric pollutants (e.g., NH_3) during storage and after land spreading of digestate (Amon et al., 2006). Acidification before an eventual solid-liquid separation has been shown as a good emission abatement practice when managing digested livestock slurries (Regueiro et al., 2016). Occurrence and fate of soil pollutants such as pathogens, heavy metals, pesticides, and hormones, which can be harmful if entering in the human food chain, has also been assessed (Govasmark et al., 2011; Rodriguez-Navas et al., 2013; Bonetta et al., 2014). Digestate handling strategies have been analyzed taking into account current legislation, nutrient management planning, local agricultural constrains, and particularities such as continuous digestate production but seasonal nutrient needs in cropping systems, among others (Flotats et al., 2009). Research studies dealing with the use of fresh digestate as source of nutrients have appeared mainly linked to agricultural systems but also to some alternative areas such as hydroponics (Krishnasamy et al., 2012), forestry (Bardule et al., 2018), and soil reclamation (Garcia-Sánchez et al., 2015). Finally, the characterization of livestock-biogas-fish farming systems, which imply integration of crop production, vegetable cultivation, livestock breeding and/or fish culturing, has been addressed in developing countries, particularly in Asia (Wu et al., 2014). Limitations in the use of fresh digestate as source of nutrients in agriculture and other similar areas have motivated the quest for processing technologies.

Research in biological nutrient removal technologies applied to anaerobic supernatants was started in the early 90's. Both intensive (based on the use of bioreactors) and extensive (including wetlands) systems have been considered (Monfet et al., 2018). "Nitrification" was the most active topic because to achieve biological N-removal, nitrification is necessary for both conventional strategies based on heterotrophic denitrification and advanced strategies based on anammox. Besides, the aerobic treatment based on nitrification can seek the transformation of N volatile species to non-volatile species and be applied in nutrient recovery strategies (Botheju et al., 2010). The energy required for aeration to complete nitrification and the organic carbon required in heterotrophic denitrification are two of the main drawbacks of the NDN technologies (Siegrist et al., 2008). In this regard, significant reductions in the requirements of energy and organic carbon have been demonstrated when the NDN process is optimized through the nitrite route (Malamis et al., 2014). Alternatively to classical N-removal, the anammox process was first reported in mid-90s by Mulder et al. (1995) and research in this field is known to speed up after the year 2000 (Magrí et al., 2013; Zhang and Liu, 2014). Hence, over the last 15 years, many technologies based on applying PN-anammox related processes have been developed and characterized in detail, and several of them are currently being implemented at full-scale (mostly addressing the sidestream treatment of reject water generated when dewatering anaerobically digested sewage sludge). In this regard, more than 100 full-scale PN-anammox installations are currently running worldwide (Lackner et al., 2014), and the number of new plants is increasing rapidly. Lately, mainstream wastewater treatment through energy efficient processes like anammox has attracted interest and has been posed as precedence for innovation and development by the water industry (Vela et al., 2015). The emission of N_2O in N-removal systems owing to the activity of both nitrifying and denitrifying microorganisms has often been addressed in research studies, as summarized by Massara et al. (2017). Other non-biological methods to achieve nutrient removal from digestate have also been reported but in a lesser extend (Fernandes et al., 2017).

The recovery of nutrients from digestates has undergone accelerated development in recent years. Research has frequently focused on the separated handling of solid and liquid fractions instead of the integrated processing of the digestate. Multiple technological alternatives have been considered as reviewed elsewhere (Fytili and Zabaniotou, 2008; Fuchs and Drosg, 2013; Sheets et al., 2015; Vaneeckhaute et al., 2017; Monfet et al., 2018) with significant particularities between N and P (Desmidt et al., 2015; Zarebska et al., 2015). Physicochemical methods usually target the production of high quality, nutrient-rich concentrates that can be placed on the market. Besides, some of these methods may help to prevent problems in AD systems such as, for instance, microbial inhibition by ammonia accumulation within the digester (Nie et al., 2015) and the formation of struvite scale deposits (Le Corre et al., 2009). Research experiences at lab-, pilot- and full-scale have been reported for technologies such as (i) precipitation / crystallization of magnesium and calcium phosphates, (ii) pressure-driven membrane filtration involving microfiltration, ultrafiltration, nanofiltration and/or reverse osmosis, (iii) NH_3 stripping followed by absorption under acidic conditions, (iv) adsorption and ion exchange, and (v) thermal treatment, among others. Biological methods have also been assessed; this includes, among others, (vermi)composting treatments applied to solid material fractions (Hanc and Vasak, 2015; Magrí and Teira-Esmatges, 2015; Zeng et al., 2016) and algae cultivation techniques applied to liquid streams (Cai et al., 2013; Monlau et al., 2015). Composting as post-treatment of the digestate forces the aerobic biodegradation of remaining organic matter, favoring the stability and maturity of the final product. An appropriate rise of temperature during the process will lead to the drying of the material and to the elimination of potential pathogens (Teglia et al., 2011). Blend of the digestate with other materials may be convenient according to its moisture content and C/N ratio. Interest in algae has grown rapidly in recent years, and technical feasibility of many applications has been demonstrated, allowing integrated biofuel production, carbon dioxide mitigation, and nutrient recovery from wastewater streams. The transformation of algae in biogas, followed by the use of the digestate for algae cultivation, enables an interesting closed-loop approach for the production of bioenergy (Prajapati et al., 2014). Owing to the change in perception of WWTPs as resource recovery facilities, conventional mathematical models started to be updated including new processes, technologies and plant layouts (Fernández-Arévalo et al., 2017). Future research in nutrient recovery should focus on innovative technologies not yet consolidated at full-scale (Bakx et al., 2009; Desmidt et al., 2015; Zarebska et al., 2015) engaging with the emerging concept of (bio)refinery which can be based on physicochemical (Dube et al., 2016), biological (Matassa et al., 2015), or bioelectrochemical processes (Hou et al., 2017), as well as on further verify and improve the characteristics and marketing value of digestates and other derived products toward agricultural and industrial end-users (Dahlin et al., 2015). As pointed out by Monlau et al. (2015), the (bio)refinery concept draws new challenges to be considered, and thus, research on sustainable digestate valorization through (bio)refinery is called to face significant development in the next years. Pilot-scale experiences will be needed to assess the real benefits in terms of energy balance, environmental impact, and economy, and to better decide on the integration of processes from an industrial point of view.

Finally, environmental and life-cycle assessment of integrated agro-energy systems (De Meester et al., 2012; Van Stappen et al., 2016) and digestate treatment technologies (Rehl and Müller, 2011; Rodriguez-Garcia et al., 2014; Vázquez-Rowe et al., 2015) is attracting increasing attention. To move toward sustainability, it will be needed the implementation of integral solutions, a reduced consumption of resources, and circular economy strategies, among other aspects, at the same time that minimizing the affectations on the environment (van Loosdrecht and Brdjanovic, 2014; Molina-Moreno et al., 2017).

CONCLUSIONS

The bibliometric analysis of the articles published in the last three decades (from 1988 to 2017) in the area of knowledge of nutrient management from digestates led to the following main conclusions:

- The annual publication rate has followed an upward trend, particularly in recent years. Only in the last three years has appeared ∼37% of the total production.
- China, USA, and Spain were the three most prolific countries regarding number of articles published. The most productive institutions were primarily European.
- Topic of the articles was mostly connected to ‘crop nutrition & fertilization’ and the characterization of ‘nutrient recovery technologies’. Despite the number of published articles dealing with ‘nutrient removal technologies’ start growing significantly in the 2000s, its trend was clearly bypassed in recent years by that of the ‘nutrient recovery technologies’. Conceptual studies, focusing on ‘environmental & life-cycle assessment’, are attracting growing attention since the period 2003–2005.
- Trends for promoting sustainability when managing nutrients from anaerobic digestates include low environmental impact, low uptake of resources, integral agro-energy solutions, and circular economy approaches based on the recovery of valuable and marketable products.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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