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Operation and Maintenance of Small-Scale Biogas Digesters: Scoping Review and Bibliometric Analysis of Literature

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Abstract

Biogas technology has matured over the years and is gaining acceptance; however, challenges with optimum operation and maintenance of digesters are a massive hurdle for developing countries that threaten the successful adoption of the technology. The failures of biogas digesters leading to the low diffusion of the technology in developing countries have been attributed to several factors spanning from social to technical. This study employed a scoping review and bibliometric analysis to synthesize literature in the Scopus database to map and discuss scientific knowledge. The synthesized data suggest the need for real-time monitoring systems for the optimal operations and maintenance of small-scale biogas digesters. A bibliometric analysis with the VOSviewer software of the study suggested that there is limited research output from developing countries such as Ghana. It, therefore, necessitates the need for conscious commitments from stakeholders to invest resources to advance research to address the challenge.

Keywords: Biogas; operations and maintenance; scoping review; real-time monitoring; bibliometric analysis; Scopus; VOSviewer**.**

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1. Introduction

Access to clean energy and efficient use via appropriate conversion technologies are essential to achieving the sustainable development goals (SDGs). The targets outlined in the SDGs 2030 are directed towards the general well-being and the survival of humanity. Over the past decades, the heavy dependence on unclean and unsustainable energy resources (fossil fuels) has been blamed for the global temperature increase resulting in extremes in weather conditions of the planet and the predicted looming future of a polluted environment [1]. The adverse environmental impact of energy generation and consumption causes climate change, air pollution, aquatic pollution, thermal pollution, and solid and liquid waste disposal, to list but a few [2]. Energy consumption has been key to the advancement of technology for the general well-being of humanity. However, the by-product or emissions generated from fossil fuels have contributed significantly to global warming, which threatens the ability of the planet to sustain life. Fossil fuels are estimated to contribute 80% of the total global energy supply [3]. Considering the adverse environmental impact and the rapid depletion of the resource, Governments and international organizations are investing in alternate energy sources to reduce the dependence on fossil resources [4]. These investments are expected to prolong the lifespan of the resource and minimize environmental impacts [5,6]. Renewable energy resource utilization technologies, development, and adoption have received attention as their exploration promises a sustainable and clean energy source replacement. The technology development and high initial financial commitment to adopting renewable energy systems have been a major hindrance [7,8]. Amidst the challenges, renewable energy (RE) sources have achieved a significant milestone in technology development and adoption, mainly in developed countries. Globally, the contribution of RE to energy supply is in the field of electrical energy generation, and the success achieved so far is encouraging. According to the IEA reports, it was estimated that RE would experience the fastest year-on-year increment starting from the 1970s (rate of more than 8%), with solar and wind being the major contributors [9]. Among the RE sources been explored, biomass conversion technologies seem to provide a one-stop solution to mitigate the looming impact of climate change and environmental pollution. Bioenergy technologies provide clean sustainable energy, soil enrichment by-product, and organic waste management solution. These benefits have led to organic waste being identified as a resource, thereby giving it local and global attention, as waste management challenges threaten flora and fauna life. Biomass is a term that refers to plant and animal materials derived directly or indirectly from the reaction of sunlight, water, and carbon dioxide (CO_2) [10]. As biomass from a biological process, typically in the photosynthesis process, plants store the sun's energy, which is further transferred to animals through diet [11,12]. Energy from biomass is broadly called bioenergy. The use of bioenergy falls into two major classifications: "traditional" and "modern." The combustion of biomass in such forms as wood, animal waste, and traditional charcoal is traditional. Modern bioenergy technologies include biofuels generated from bagasse and other organic materials through; biorefineries, anaerobic digestion of residues, heating systems for wood pellets, and other technologies [13]. For centuries, biomass has been used to meet energy requirements, especially heating. In recent times biofuels are considered sustainable alternatives for transport and electricity generation. Biogas is a rich methane (CH_4) content ranging from 45% to 75% by volume of flammable gas [14] generated from the decomposition of organic matter by microorganisms (fungi, archaea, bacteria, and other decomposer organisms) in a wet favorable condition. Soil humus and essential plant nutrients are by-products of the decompositions of organic matter in biogas production. The process is

accomplished by different species of microorganisms grouped as anaerobic (absence of oxygen) [15]. The aerobic decaying of the organic matter releases an insignificant amount of heat, and carbons are completely oxidized to CO_2. Therefore, aerobic digestion of biomass is not a useful energy supply process [16].

On the other hand, anaerobic decay or digestion of biomass in an air-tight environment breaks down carbohydrates by the action of anaerobic bacteria to release biogas. Nutrient-rich fertilizer is developed in the process. Carbon can either be fully oxidized into CO_2 or reduced into CH_4. Depending on the feedstock, studies have also estimated biogas to consist of 60–70% methane (CH_4), 30–40% carbon dioxide (CO_2), together with trace gases, i.e., nitrogen (N_2), hydrogen (H_2), hydrogen sulfide (H_2 S), ammonia (NH_3), as well as water vapor [17]. The technology is used to construct and control the digestion of biomass to promote the generation of methane and the extraction of digested feedstock (liquid slurries). When released into the environment, the slurry or digested effluent form poses minimal health hazards as most but not all pathogens are destroyed in the digestion process.For this reason, the technology is favored as an economical and environmental solution to organic waste management problems. The potential of this technology is explored for the safe management of municipal organic waste, food processing waste, and waste from intensive animal house boundary establishment. By so doing, stringent environmental regulations are met to avoid penalties for pollution. This benefit serves as a major incentive for investment in anaerobic digesters [18–22]. The history of biogas digesters in Africa started in the 1950s in South Africa and Kenya. In other countries such as Tanzania, biogas digesters were first introduced in 1975 and, even more recently, in South Sudan. The interest in biogas technology in Africa has been accelerated by the promotion efforts of various international organizations and foreign aid agencies [23,24].Three popular types of biogas technologies designed, tested, and used are the fixed-dome, floating drum, and puxin digester in Ghana. These designs do not vary greatly, and digesters are constructed with concrete or bricks. The puxin digester uses molds to build the digester and some prefabricated parts. Biogas technology deployment has a vast potential and offers both developed and developing countries the opportunity to meet their renewable energy mix targets such as Ghana. Biogas technology deployment has a vast potential and offers Ghana the opportunity to meet its 10% renewable energy mix target It would further increase the country's chance of achieving Sustainable Development Goals (SDGs). The national renewable energy master plan outlines government commitment to promote and support renewable energy deployment in the country. Waste-to-energy conversion technologies captured in the plan seem not to get the necessary emphasis as the estimated installed systems do not reflect the potential of the technology in the country [25]. The installations of biogas technology (biogas digesters) is over three decades old, with expectations still unmet due to varied challenges. The technology, however, has seen acceptance and success in other countries and even expanded to commercial biogas production. There are voluminous published data on biogas technologies; however, information available on the operation and maintenance of biogas systems in the developing world where these technologies can make a difference has not been synthesized. It has necessitated conducting a scoping review and bibliometrics analysis to systematically map research on the subject and report on the synthesized knowledge to direct further studies. The study aims to map knowledge available on the operation and maintenance of biogas digesters in a database to get a bird's eye view of the extent of work on the issue with a focus on Ghana, a developing country. This study is preliminary research guided by the objectives; 1) identifying available literature on the operation and maintenance of biogas. 2) To synthesize knowledge to

inform further studies, 3) To assess researchers' contribution to the subject, 4) To identify what research collaboration exists with other countries, and 5) to identify current and future research trends on the topic under study.

2. Methods

Knowledge synthesis types/methods have been developed and used in the medical sciences for a while now and steadily gaining acceptance in other fields [26,27,36,37,28–35]. To achieve this study's outlined objectives (1 &2), the PRISMA Extension for Scoping Reviews (PRISMA-ScR) was used. PRISMA- ScR is a type of knowledge synthesis which follows a systematic approach to map evidence on a topic and identify key concepts, theories, sources, and knowledge gaps [38]. The second method – bibliometric analysis, was employed to analyze the knowledge domains, collaborations and possible future research trends on retrieved data for objectives (3, 4 and 5). The framework developed initially by Arksey and O'Malley [39] on scoping review was adopted for the study.

2.1 Scoping review

2.1.1 Identifying electronic database and eligibility criteria

Publications for the study were selected based on the PRISMA-ScR [38]. This section is presented using the PRISMA-ScR items list presented as subheadings. The Scopus database was selected for the study as it has more information and data sets that are faster to process. The database chosen has a stringent indexing procedure for documents, and the retrieval of bibliometric data is convenient. Furthermore, researchers have reported on the database's rigor, quality, and robustness and contain a significant percentage of information found in other databases (Thompson Reuters, Web of Science, Google Scholar, Dimensions, etc.) [28,36,31]. The search data was exported as comma-separated values (.csv) file for further processing in Microsoft office excel. The inclusion and exclusion criteria are summarized in Table 1.

Table 1: Eligibility criteria for document selection

Inclusion Criteria
Articles published in English
Selected period 01/01/1979 to 31/12/2021
The research focused on biogas digesters
Types of documents are articles, conference papers, reviews, and book chapters peer-reviewed
Studies focused on the operation and maintenance of biogas
Exclusion Criteria
Studies that do not relate to the operation of biogas digesters
Articles without access to the full text
Articles without clear linkage to the operation and maintenance of biogas digesters
Duplicate entry
Articles with missing bibliometric data

2.1.2 Screening and selection of publications

The advanced search on the Scopus database (www.scopus.com) was carried out using the article title, abstract, and keywords. This was guided by an iteratively constructed comprehensive list of primary and secondary key terms, connected using Boolean logic and filtered to include as many research articles as feasible that were relevant to the study's aims. The primary search phrases were those that often appeared in the literature regarding biogas technology installations. The publication year, subject area, document format, and articles published exclusively in English were all used to filter the final documents. The search string used is given below;

TITLE-ABS-KEY ("Improving the operation" OR "abandonment" OR "failures" OR "household" OR "methane" OR "Africa" OR "develop ing" OR "countries" OR "biomethane" OR "green energy" OR "environment" OR "pH" OR "temperature" OR "effecting factors" OR "household digest*" OR "clean cooking fuel" OR "domestic cooking fuel" OR "rural" OR "fertili*" OR "manure" OR "livestock" OR "Biogas plant" OR "gas production" OR "utiliz* " OR "electric* power generat* " OR "crops" OR "maintenance" OR "digest*" OR "biomass" OR "small-scale" OR "Anaerobic digest*" OR "Waste management" AND "biogas digest*") AND (EXCLUDE (PUBYEAR , 2022)) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (LANGUAGE , "German"))

2.2 Bibliometric analysis

The bibliometric analysis technique employed performs two main functions; performance analysis and science mapping. Performance analysis assesses the inputs of research constituents, while on the other hand, science mapping considers the research constituents' relationships on a given subject [40]. Bibliometric mapping analysis was conducted using the VOSviewer software program, which is used to quantify and visualize the contributions of researchers in the scientific community [41,42,43]. The software analyzes terms, trends, associated concepts, and collaborative network maps. Performance analysis and science mapping were conducted using the guidelines proposed by Naveen and his colleagues [40].

2.3 Data selection and screening

The search string used was the same as aforementioned and screened using the inclusion and exclusion criteria illustrated in Table 1. Additionally, studies were categorized into feedstock, socio-economic, state of development and adoption, design and construction, policies/interventions, biogas and digestate use, operation and maintenance, and hybrid system (biogas digester/solar systems). Figure 1 presents the flowchart diagram of the activity sequence for handling data of the bibliometric analysis.

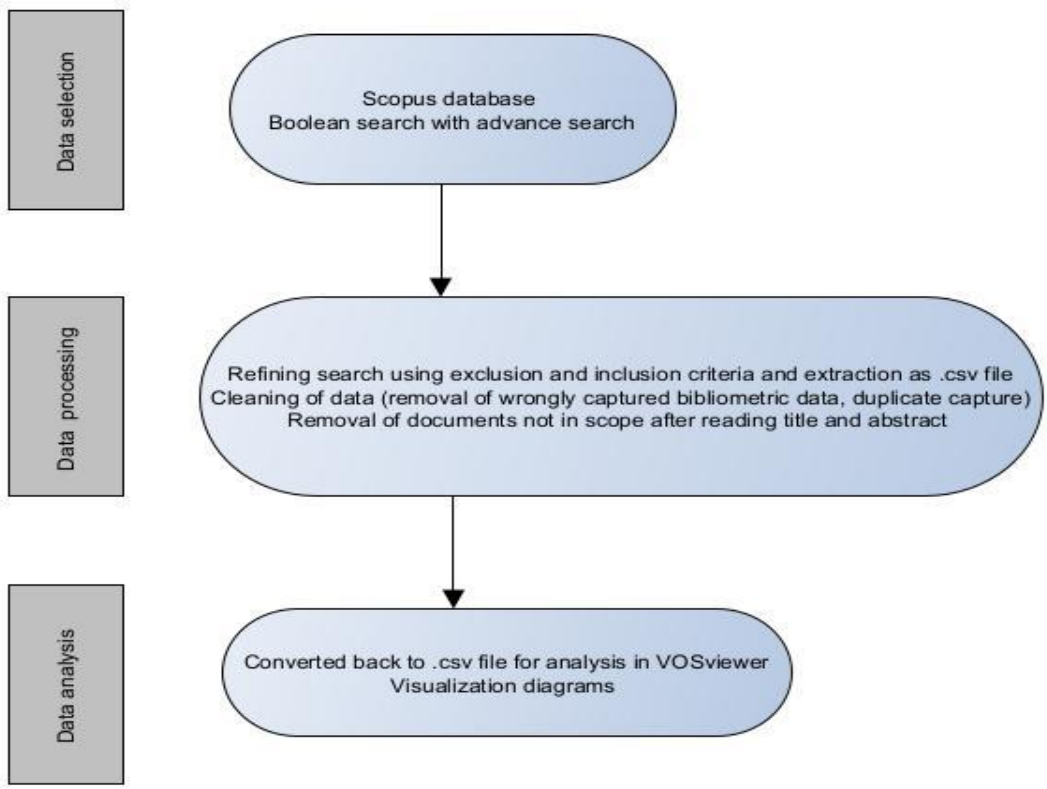

Figure 1: Flow diagram for method and analysis

2.4 Research contents' analysis matrix

The primary technique of bibliometric analysis employed in the study was science mapping, as summarized in Figure 2. The study considered research contents such as authors, country, and journal contributions to the Scopus database on biogas technology. The most frequently used metrics are publications and citations per year or research content, with publication as a proxy for productivity and citations as a measure of impact and influence. Additionally, other metrics, such as citations per publication and the h-index, combined citations and publications to assess the performance of research elements can be done with this method.

Co-authorship among authors promotes knowledge sharing with the potential of improving research and sheds light on the challenges of the subject in underrepresented regions like Africa in the research space. Co-authorship analysis was conducted on the selected documents from the search to assess the interaction among scholars in the field to assess intellectual collaboration. The ten most-cited articles/journals were presented with their corresponding publication characteristics.

For the objective (3, 4 & 5) of this study, VOSviewer software was used as it is an excellent tool for data visualization and network creation. VOSviewer is a software application that supports the creation of maps based on network data and the visualization and exploration of these maps. Network creation and visualization of maps require bibliographic database files (e.g., Web of Science, Scopus, Dimensions, Lens, and PubMed files) and reference management files (e.g., RIS, EndNote, and RefWorks files) to be uploaded into the

software. VOSviewer presents science mapping networks for bibliometrics using a distance-based approach for visualization as 'nodes' and 'edges' with varied interpretations based on the network presented. The analysis of networks of the study was based on three (3) considerations as in the studies of [33,40]. Microsoft Excel was used for data cleaning and graphs creation. A summary of the analysis parameters of the main bibliometric analysis techniques of the study is presented in Figure 2, as proposed by Naveen and his colleagues [40].

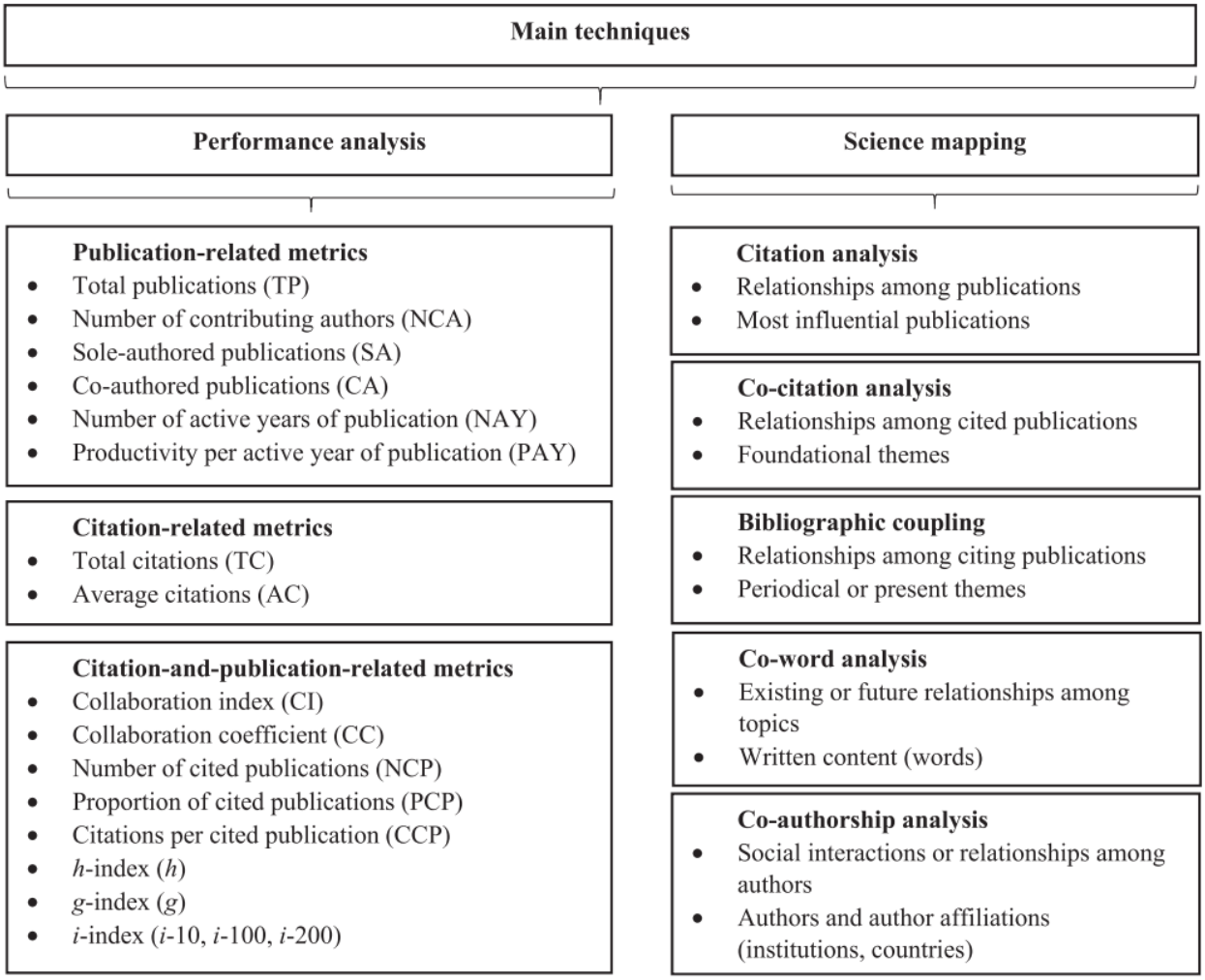

Figure 2: Bibliometric analysis toolbox [40]

3. Results and discussions

This section of the study presents the results and draws inferences to advance the understanding of the subject along the two methods adopted (scoping and bibliometric). As aforementioned, the method adopted for the study is relatively new in this subject area and hence making comparison with previous studies is a challenge. We have however, attempted to link our results and discussions to relevant documents.

3.1 Scoping review

The search string used in the Scopus database initially generated 867 articles. Before reviewing the entire

content, the titles and abstracts of the retrieved publications were reviewed to determine their eligibility. The complete text of all possibly qualified articles were subsequently reviewed to decide whether or not they should be included. The preliminary cleaning of bibliometric data resulted in the exclusion of 813 articles. These articles were excluded because of missing/inconsistent bibliometric data or not meeting the study's objectives. A total of 36 articles met all the criteria specified in the screening criteria for full-text screening. However, only fifteen (15) articles from the 36 qualified articles had full-text screening because they were accessible. The PRISMA flow diagram for the selection [39] shows below (Figure 3).

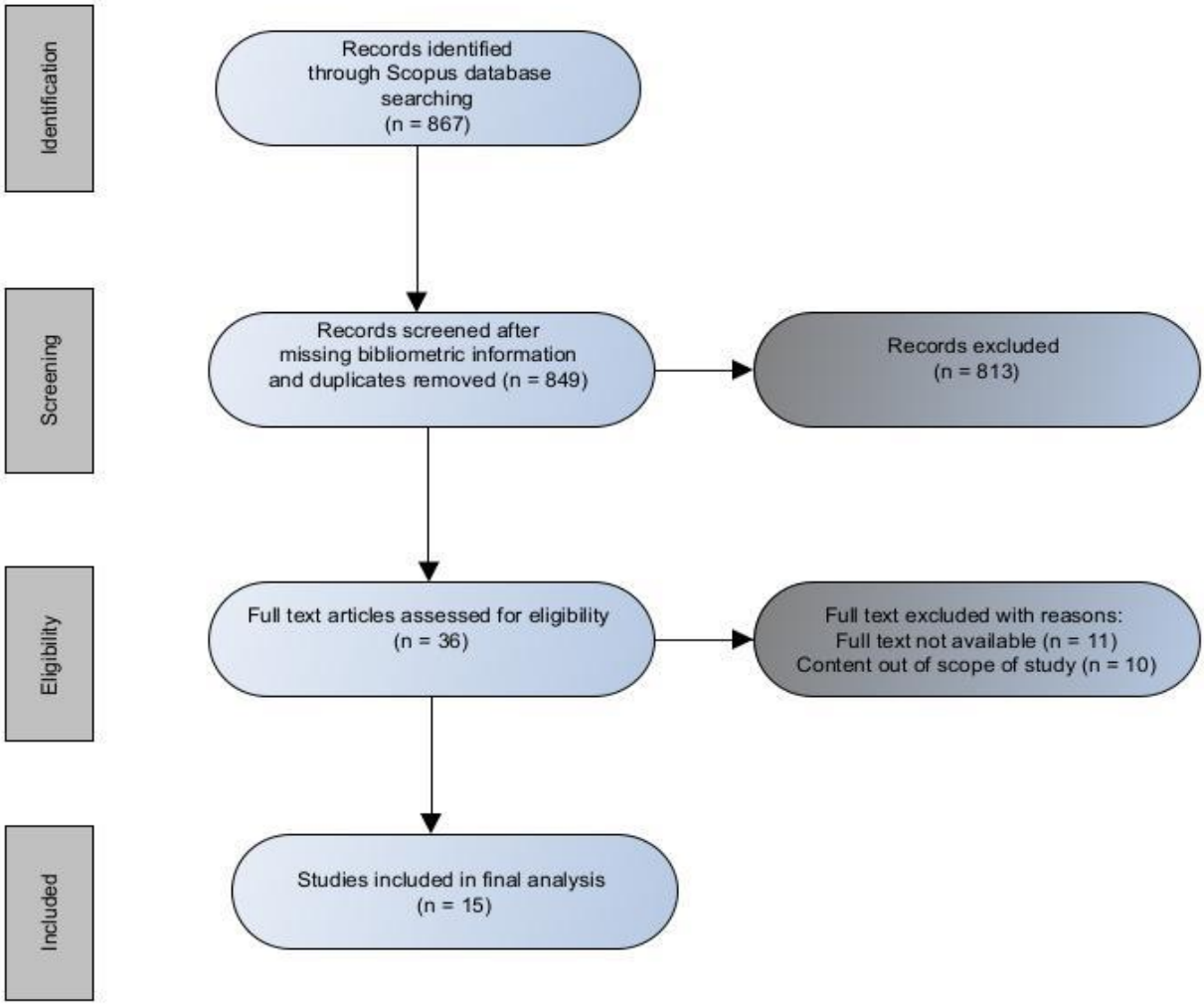

Figure 3: PRISMA-Sr flowchart diagram

3.1.1 Data charting

According to Arksey and O'Malley's scoping review framework, studies that met the eligibility criteria were charted. The charting form was developed to capture variables such as author(s), titles of studies, publication year, country of the first author, objective(s) of study, methods and outcome/findings. The data chart was reviewed and verified by two (2) independent reviewers. The charted data was discussed continuously to ensure data met the selection criteria in an iterative process using a Microsoft Excel datasheet. Table 2 presents a summary of the articles reviewed.

Table 2: Scoping results summarized according to Arksey and O' Malley's framework

S/N	Author(s)	Title	Year/Country of the first author	Objectives	Methods	Key findings	Cite
1	A. Kleybocker, T. Lienen, M. Liebrich, M. Kasina, M. Kraume, H. Wurdemann	Application of an early warning indicator and CaO to maximize the time–space-yield of an completely mixed waste digester using rape seed oil as co-substrate	2013, Germany	The purpose of the study described in the paper was to run a laboratory-scale biogas digester at high OLRs using the EWI-VFA/Ca in conjunction with the addition of CaO. In order to research the impacts of the OLR rise and the additive addition, the composition of the microbial community was observed throughout the experiment.	The EWI-VFA/Ca is used to monitor and regulate process efficiency as well as to precisely dose additives to maximize space yield. By using EWI-VFA/Ca, CaO, the laboratory-scale biogas digester was prevented against over acidification. WTW pH 340i and a Sen Tix 41 pH electrode were used to measure the temperature and pH of digested sludge samples, as reported by Kle-ybocker	The EWI-VFA/Ca detected any imbalance in process performance early enough for effective remedies to be implemented, hence permitting the gradual growth of OLR and limiting the danger of process failure. Calcium oxide was an effective process stability additive. The implementation of EWI-VFA/Ca to adjust additive dose and control the biogas generation process was shown to be an adequate method for maintaining process stability.	[44]
2	Angelidaki, L. Ellegaard, B. K. Ahring	Compact Automated Displacement Gas Metering System for Measurement of Low Gas Rates from Laboratory Fermentors	1991, Denmark	To build an automated metering system to measure biogas production from laboratory-scale biogas digesters	Two standard graded cylinders were utilized to produce the gas meter's gas chamber. A liquid optical sensor, a two-way pinch valve, a resettable electromechanical counter, an electronic control circuit, tubes and fittings, and a power supply are all components of the system (12-15DCV).	A less dependable gas flow meter suitable for experimentation was developed. Corrosion-resistant materials were used to automate the procedure.	[45]

3	Richard Arthur, Paul A. Scherer	Monitoring dissolved active trace elements in biogas plants using total reflection X-ray fluorescence spectrometry	2020, Ghana	To employ total reflection X-ray fluorescence (TXRF) to monitor the dissolved, active components in biogas facilities at g/L concentrations. .	The reference material was a single charge, certified barley straw reference material "WEPAL IPE 680" from LGC Standards GmbH (Wesel, Germany). TXRF spectroscopy was used to calibrate the wheat straw substrate in order to ascertain its entire elemental composition. Standard solution contained Cobalt (Co), Nickel (Ni), Tungsten (W), Selenium (Se), and Gallium (Ga) (gallium). Three methods were employed (direct analysis, pretreatment with microwave-assisted acid, and concentrated HNO_3	The use of TXRF spectroscopy to monitor trace components in a biogas production is a cost-effective management technique that enhances process stability. .	[46]
4	L. Castro, H. Escalante, J. Jaimes-Estévez, L.J. Díaz, K. Vecino, G. Rojas, L. Mantilla	Low-cost digester monitoring under realistic conditions: rural use of biogas and digestate quality	2017, Colombia	To evaluate the behavior of anaerobic digestion of cattle dung in a rural digester under realistic settings and to determine the digestate's quality and characteristics.	Characterization and microbiological examination of digestate for quality evaluation. With tubular polyethylene, a low-cost digester was developed (caliber 8 and UV protection). Over the course of four months, the performance of AD in a continuous tube digester was monitored. The process's stability was tested utilizing the VFA/TA ratio and pH. Energy and economic considerations led to a comparison between biogas with commercial gas (propane).	Monitoring data suggested that the functioning of the digester was stable and without risk of inhibition. It generated an average of 0.85 Nm^3/d of biogas containing 65.6% methane, resulting in a 76% reduction in energy use. The digestate contains significant quantities of nutrients, which is a crucial characteristic of fertilizers. However, post-treatment is necessary due to the presence of microorganisms. .	[47]

5	Dukuzumuremyi Dieudonne and Hisato Shima	Effectiveness of applying IoT to Improve Biogas digesters in Rwanda	2018, Japan	This study aims to develop and deploy an IoT (Internet of Things) system to optimize biogas digesters by providing accurate data from inside and outside digesters in real-time via sensor technologies and a web-based framework.	Design and construction of a remote and real-time tracking system. On a Esp8266 Arduino module powered by solar PV and interfacing with a web-based platform, sensors were utilized to measure the digester's temperature and humidity.	The collected data would assist digester operators in managing the systems to guarantee process stability for maximum gas yield and redesigning digester designs for enhanced performance.	[48]
6	Christina Huck, Arshak Poghossian, Iman Kerroumi, Sebastian Schusser, Matthias Bcker, Willi Zander, J rgen Schubert, Vahe V. Buniatyan,Norayr W. Martirosyan, Patrick Wagner, and Michael J. Schçning	Multiparameter Sensor Chip with Barium Strontium Titanate as Multipurpose Material	2014, Germany	Using barium strontium titanate (BST) as a multifunctional material, a sensor chip for the multiparameter detection of three physicochemical parameters such as electrolyte conductivity, pH and temperature is fabricated and tested.	Fabrication of a Multiparameter Sensor Chip that combines three sensors for detecting conductivity, pH value, and temperature, thereby merging various transducer concepts on a single chip. As an electrolyte-conductivity sensor, four thin-film Pt electrodes were employed. Exemplary testing of the sensor chip was conducted in a methane digester.	The four-electrode electrolyte conductivity sensor demonstrates outstanding linearity in the range of 0.084 mS/cm to 50 mS/cm electrolyte conductivities. The pH sensor demonstrates a near-Nernstian pH sensitivity of S=57.4 mV/pH between pH 3 and pH 11. The temperature sensor has a linear temperature calibration curve from 20 to 408 degrees Celsius with a temperature coefficient of a=0.0034 degrees Celsius.	[49]
7	Vidyarani S. Kshirsagar and Prashant M. Pawar	Design optimization of biogas digester for performance improvement and fault minimization	2018, India	To investigate a passive method for enhancing velocity patterns by supplying static flaps of suitable size and position. .	The design optimization problem is formulated to maximize the surface and domain velocities in the digester by altering the flaps' geometries and positions. The numerical results obtained	The efficiency and fault tolerance of the biogas plant are dependent on the digester's sludge mixture. On the basis of the velocity profile in the digester, the quality of mixing can be	[50]

					using the CFD and optimization tools of the software COMSOL Multiphysics illustrate this strategy.	evaluated statistically.	
8	Cuong H. Pham, Jin M. Triolo, Sven G. Sommer	Predicting methane production in simple and unheated biogas digesters at low temperatures	2014, Denmark	The objective of this study was to build kinetic models for predicting methane production in such situations by measuring specific methane productivity in biogas digesters under psychrophilic (20 C) and psychrotrophic (20–30 C) environments.	In Vietnam, a large-scale field investigation was conducted in four continuous biogas digesters with a hydraulic retention time (HRT) of 40 days. Afterward, the models were validated using the data. R^2 of projected against measured production was 0.79 when pooled weekly mean data were utilized for forecasting.	In order to predict methane output in unheated biogas digesters, models were devised. In simple, unheated methane digesters, temperatures above 20 °C were necessary. Using the pooled monthly mean data, the model achieved a high level of accuracy. Pig manure methane production prediction algorithms were good.	[51]
9	Daniela Polag, Lutz Christian Krapf, Hauke Heuwinkel, Stephan Laukenmann, Jos Lelieveld, Frank Keppler	Stable carbon isotopes of methane for real-time process monitoring in anaerobic digesters	2013, Germany	Evaluation of an online measurement technique (laser absorption spectroscopy) for real-time monitoring of stable carbon isotopes of methane (13CCH4) in a pilot-scale (3500 L) biogas digester routinely fed with maize silage.	As a novel strategy, we implemented an online measurement technique (laser absorption spectroscopy) for real-time monitoring of stable carbon isotopes of methane (13CCH4) in a pilot-scale biogas digester (3500 L) routinely fed with maize silage.	The initial findings of a 2-week monitoring experiment indicate that stable carbon isotopes of methane respond rapidly and are highly dynamic in response to changes in the digester's process state. In conjunction with other monitoring data (methane production rate, concentration of volatile fatty acids, and pH), variations in 13CCH4 can be interpreted as a change in methanogenic pathways caused by a high organic loading rate. In this situation, 13CCH4 might be employed as a new parameter tool for monitoring and	[52]

						characterizing the digester's process condition.	
10	Andrea Stockl, Hans Oechsner	Near-infrared spectroscopic online monitoring of process stability in biogas plants	2012, Germany	Online near-infrared reflection spectroscopy (NIRS) monitoring of biogas digester process stability. This study details the construction of NIRS calibrations for the concentrations of acetic acid equivalents, acetic acid, and propionic acid in digester substrate.	Using experimental biogas digesters with mesophilic and thermophilic operation and support vector regression, calibration models were developed by increasing acid concentrations artificially and applying support vector regression.	The values given demonstrate the viability of NIRS calibration. The ratio of standard deviation and standard error of prediction (RPD) for the parameter acetic acid in the thermophilic digester was determined to be 3.21. The RPD for the similar acid in a mesophilic digester was 4.91. For the parameter propionic acid, calibration models with RPD values of 4.23 and 4.78 were achieved for the thermophilic- and mesophilic-operated digesters, respectively	[53]
11	Andrea Stockl, Fabian Lichti	Near-infrared spectroscopy (NIRS) for a real-time monitoring of the biogas process	2017, Germany	Evaluation of Near-infrared spectroscopy (NIRS) for monitoring the concentration of specific process parameters during anaerobic digestion.	A laboratory-scale biogas digester was continuously fed maize and grass silage every four hours to maintain a 2.5 kg oDM/m^3 d organic loading rate (OLR). Daily impact loads with shredded wheat up to 8 kg oDM/m^3 d were added to achieve peaks at the investigated values. .	Changes in process parameters such as volatile fatty acids (VFA), propionic acid, total inorganic carbon (TIC), and the ratio of volatile fatty acids to the carbonate buffer (VFA/TIC) can be displayed by the created calibration models. The values could be predicted with an R^2 of 0.94 and 0.97, respectively, based on the calibration of the models for VFA and TIC. VFA and TIC had residual prediction deviations of 4.0 and 6.0, respectively.	[54]

12	Xuemei Wang, Xue Bai, Zifu Li, Xiaoqin Zhou, Shikun Cheng, Jiachen Sun, Ting Liu	Evaluation of artificial neural network models for online monitoring of alkalinity in anaerobic co-digestion system	2018, China	To create an alkalinity modeling technique for online monitoring utilizing an artificial neural network (ANN)	The software sensor technique for online alkalinity monitoring was investigated. Method for soft sensors based on an artificial neural network (ANN). The pH, ORP, and EC variables were chosen as inputs for the alkalinity prediction model.	The ideal model for an artificial neural network had a 3-2-1 structure and an R^2 value of 0.9948. ORP was the most important model factor with the highest degree of sensitivity. The coefficient of determination (R^2) was calculated to be 0.9948. ORP is the most significant model element with the highest degree of sensitivity.	[55]
13	Alastair James Ward , Emiliano Bruni , Morten K. Lykkegaard , Anders Feilberg , Anders P.S. Adamsen , Anders P. Jensen , Allan K. Poulsen	Real time monitoring of a biogas digester with gas chromatography, near-infrared spectroscopy, and membrane-inlet mass spectrometry	2011, Denmark	To compare online monitoring approaches for process parameters in the liquid and gas phases of a pilot-scale anaerobic digester.	1. A pH probe connected to data acquisition software. 2. A near-infrared spectrometer equipped with a diffuse reflectance probe situated in a re-circulation loop to monitor VFA in the liquid phase. 3. A MIMS to measure various gases in the headspace. 4. A l-GC, calibrated for H_2, CH_4, CO_2, H_2S, N_2, and O_2 measurements in the headspace.	Micro Gas Chromatography accurately measured H_2, CH_4, H_2S, N_2, and O_2 in the headspace, whereas MIMS accurately measured CH_4, CO_2, H_2S, reduced organic sulfur compounds, and p-cresol. NIRS was found to be suitable for estimating acetate concentrations in the liquid phase. propionate, and total volatile fatty acids (VFA), but the prediction error was too large for accurate quantification.l-GC and NIRS were both low-maintenance techniques, while MIMS required frequent cleaning and background measurements.	[56]

14	Carl Frederik Werner, Christoph Krumbe, Katharina Schumacher, Simone Groebel, Heiko Spelthahn, Michael Stellberg, Torsten Wagner, Tatsuo Yoshinobu, Thorsten Selmer, Michael Keusgen, Marcus E. M. Baumann, and Michael J. Schoning	Determination of the extracellular acidification of Escherichia coli by a light-addressable potentiometric sensor	2011, Germany	Using a light-addressed potentiometric sensor, quantify the extracellular acidity of biodigester organisms (LAPS)	The extracellular acidity of these species may be determined using a light-addressable potentiometric sensor (LAPS).	The organisms on the sensor surface have been immobilized using a polyacrylamide-based immobilization procedure. When assessing the influence of immobilization on the extracellular acidification rate, it was demonstrated that the activity of E. coli in polyacrylamide was comparable to that in suspension.	[57]
15	H. Abu Qdais , K. Bani Hani, N. Shatnawi	Modeling and optimization of biogas production from a waste	2009, Jordan	This study employs ANN and GA to simulate and optimize the biogas production process at the Russaifah biogas facility in Jordan.	177 days of the plant's operational data were collected and utilized in the analysis. The study investigated the impact of digester operational parameters, including temperature (T), total solids (TS), total volatile solids (TVS), and pH, on biogas yield. A two-hidden-layer multi-layer ANN model was trained to simulate digester operation and predict methane generation.	The performance of the ANN model is validated, and a correlation coefficient of 0.87 confirms the model's accuracy in predicting methane output. The generated ANN model was employed in conjunction with a genetic algorithm to maximize the methane size. The optimal level of methane was determined to be 77 percent, which is larger than the plant records' maximum value of 70,1 percent. The ideal operational conditions for methane generation were established to be 36 C temperature, TS 6.6 percent, TVS 52.8 percent, and pH 6.4.	[58]

Note: EWI-VFA/Ca = Early Warning Indicator – Volatile Fatty Acid / Calcium, OLR= Organic Loading Rate, DCV= Direct Current Voltage, AD = Anaerobic Digester, UV= Ultraviolet, CFD=Computational Fluid Dynamics, MIMS= Membrane Inlet Mass Spectrometry, ANN=Artificial neural networks

Understanding the parameters that affect the process stability of the anaerobic digestion of biomass is crucial for the optimum operation of the digester. Table 2 gives an insight into the motivation and findings of the published documents considered in the study. It sheds light on the current limitations of the operation and maintenance of small-scale biodigesters, where key performance indicators have to be tested in the laboratory before an action is taken. Although the authors employed experimental methods for their studies, each had varied parameters of interest to investigate, ranging from biochemical characteristics, and microbial community to physical quantity such as pH, temperature, organic loading rate (OLR), etc

Most of the study designs were laboratory-scale designs except for the work of Dukuzumuremyi and Hisato [48] and Cuong and his colleagues [51], who demonstrated the operation of their proposed system in the field. The results of studies captured in this study were satisfactory based on the objectives set. However, field testing of proposed strategies is vital in validating the system's capability. It is not within the scope of this study to present a list of the most appropriate methods in terms of ruggedness and reliability for operation and maintenance. It is worth mentioning that real-time monitoring of some parameters of the process of anaerobic digestion is crucial in understanding the operations and maintenance of digesters. Experimental design approaches were the most favored by authors with the application of information communication technology systems to enhance system operation.

Despite the complexity of the anaerobic digestion processes, which depend on external environmental factors, socio-economics, and digester type, the studies reviewed in this work were not explicit on the workability of their proposed systems. Considering the different design types of biogas digesters, proposed solutions suggested in the documents reviewed would be enhanced if the applicability to specific designs type were stated for further studies. The low adoption of biogas technology in the developing world is attributed chiefly to the high initial cost, operations, and maintenance challenges[59]. The studies captured in our scoping review did not consider the cost implication of the design and strategies for its acceptance. Furthermore, the study results suggest that limited research in developing countries such as Ghana could be a contributing factor to the failures of the technology. It can be seen that only one (1) study area was in Africa (Rwanda)and that particular research was conducted by Japanese authors. Elsewhere in our analysis, it was found that a Ghanaian author lead one study on biogas production but in Germany. These findings further emphasize the lack of interest in resource investment in biodigester research to promote the technology's development in the subregion.

3.2 Bibliometric analysis

3.2.1 The trend of publications and citation

After screening and cleaning the extracted (867) data set, 725 publications were considered for the bibliometric

science mapping analysis of the study. A graph of the total yearly publication, total yearly citation, and normalized average citation on biogas technology is shown in Figure 4. The graphical representations suggested no significant publications on the technology (two (2) documents in 1979) until 2008 when there was a sharp increase in publication with 15 publications. The rapid growth in published articles suggests increased research interest in the technology. A similar trend is observed for the total yearly citations; however, there has been a drop in the total yearly citations in recent years which can be attributed to the time required to accumulate citations. The general growing interest trend observed in the graphical representation (Figure 4) could be attributed to the commitments of stakeholders to promote clean energy while solving the sanitation challenges.

Figure 5 summarises the number of publications in various categories of the search string, giving further insight into the interest and number of contribution of researchers to the categaried sections of biogas technology. The extracted data were categorized into subtitles as aforementioned, using the document title and abstract to understand the research trend better. The categorization reveals that most studies were focused mainly on feedstock suitability, digestate usage, and socio-economic/state of development, with a combined percentage of 79%. In as much as these categories are essential to the development and promotion of the technology, understanding the challenges of operation and maintenance of digesters is crucial and requires further investigation.

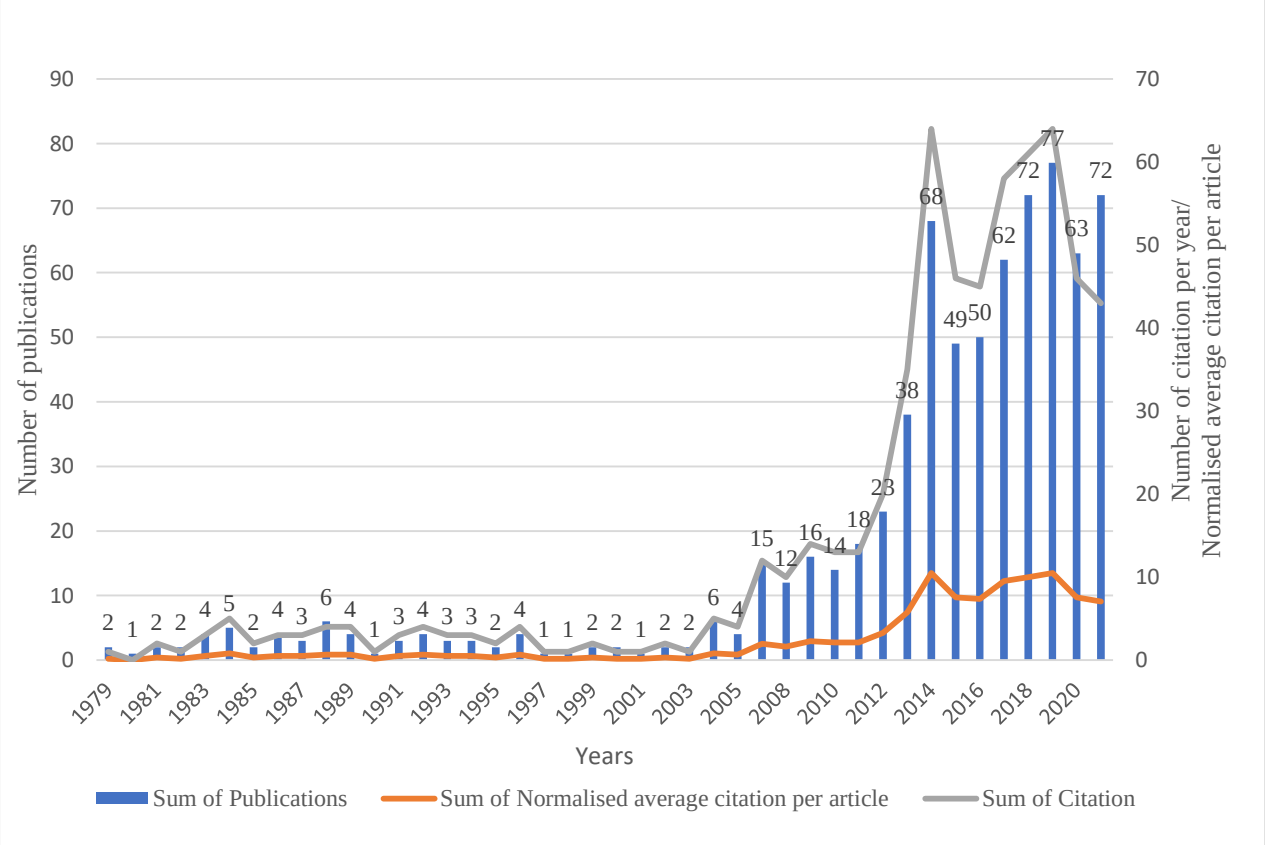

Figure 4: Yearly publications and citation trend

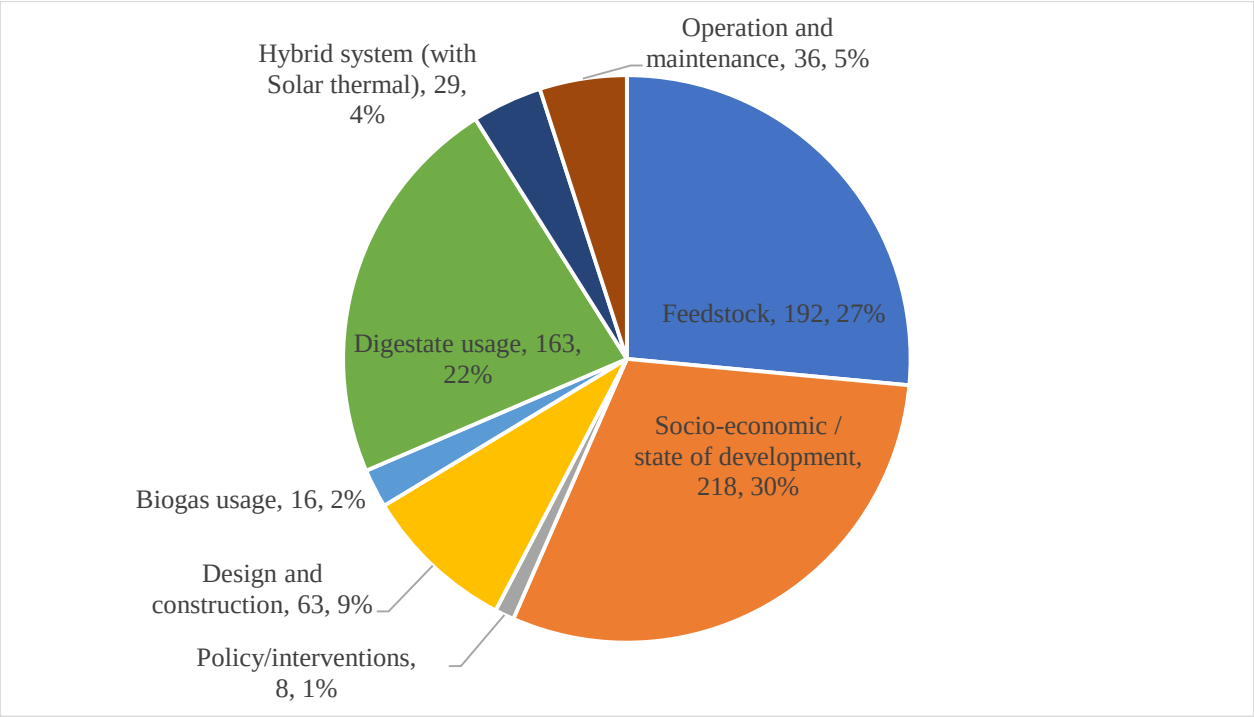

Figure 5: Pie chart on categories of research areas

3.2.2 Research contributions and collaboration of countries

Figure 6 shows the contributions of various countries on biogas technology. A total of ninety-six (96) countries were identified to have contributed to the data extracted. A minimum threshold of five (5) publications set reduced the number of countries to thirty-four (34), as shown in Figure 6. China was the most prolific contributor with 146 publications, and Estonia with the least contribution of five (5) publications. Other noticeable contributors are Germany, India, the United States, and South Africa. The research output identified by the study confirms reports on the contributions of these countries in the development and promotion of biogas technology globally via various research and funding institutions[60–68,69].

Identifying the research efforts and collaborations among researchers in a given field facilitates knowledge sharing, which is key to the successful diffusion of a technology. The network diagram of collaboration among authors from countries displayed as six (6) clusters, presents interesting results (Figure 7). Of the first five (5) prolific countries in the data set extracted, authors in Ghana collaborated with Germany and the United States of America with a total link strength of 10. There was no collaboration between Chinese authors and Ghanaian authors on the subject. Ghanaian authors also collaborated with other countries such as Uganda, Norway, the United Kingdom, and the Netherlands.

Furthermore, the data processing in VOSviewer showed that Ghanaians authored Nine (9) documents from the 725 documents as first authors. It is worth noting that only six (6) African countries are represented on the map with limited collaborations, further emphasizing that the continent is underrepresented in the biogas production research

space. An increase in collaboration between African countries and countries where biogas technology is matured would significantly contribute to addressing the challenges (installation, maintenance, operation, cost, etc) in the continent with biogas technology development and diffusion.

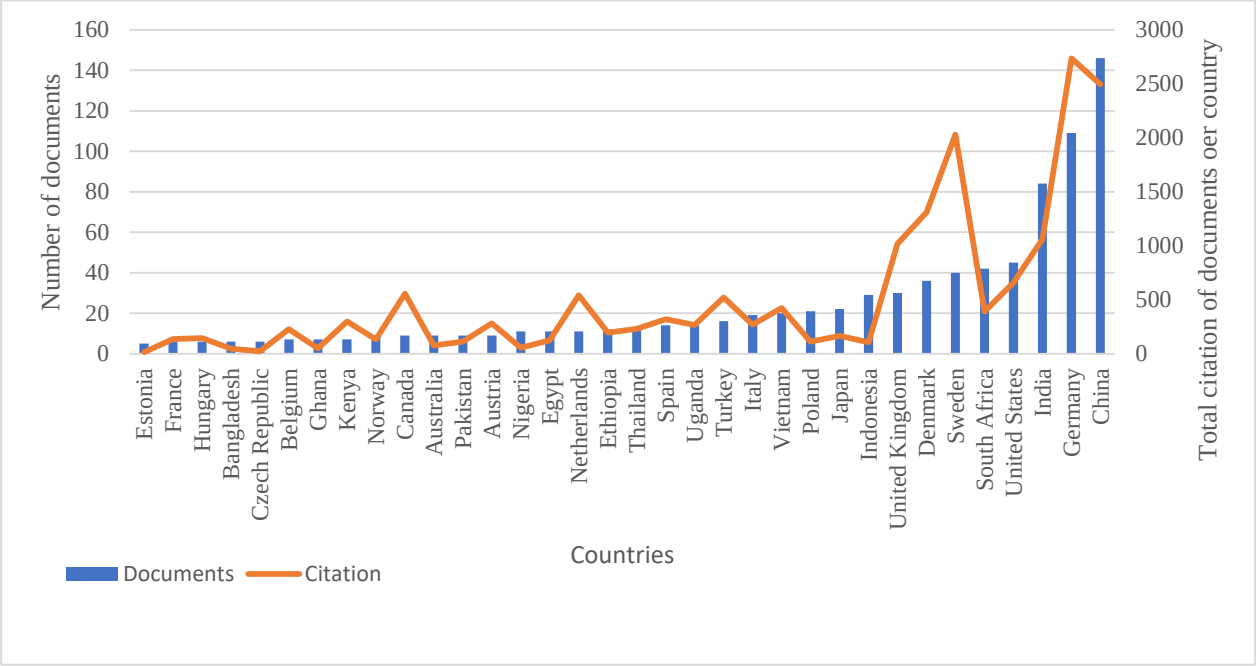

Figure 6: Total publications per country with a minimum threshold of five (5) publications

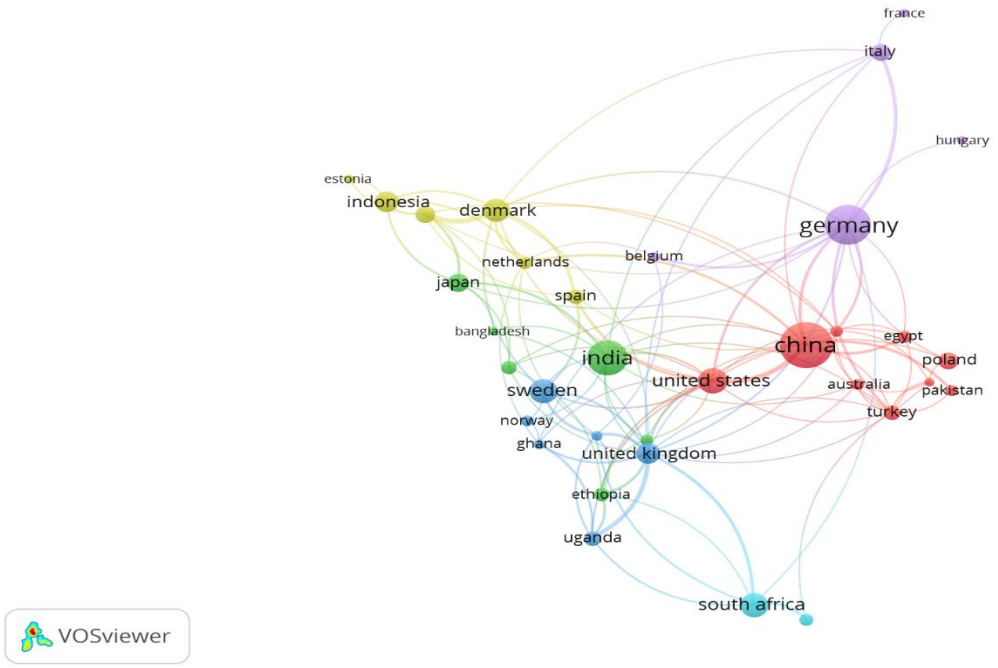

Figure 7: Collaboration network of countries

3.2.3 Co-occurrence of author's keyword analysis

The author's keywords are an important indication of their research interest and priorities in their chosen field of study [70]. The keywords further validate the dataset extracted concerning the objectives of the current study. For this reason, the author's keyword analysis was crucial to this study. A minimum threshold of five (5) occurrences was specified for a keyword to be considered in the Vosviewer software network diagram. Of 1890 identified keywords, 64 distinct keywords appeared at least five (5) times in the extracted database. The co-occurrence network diagram of the frequently used keywords is illustrated in Figure 8 as eight (8) clusters.

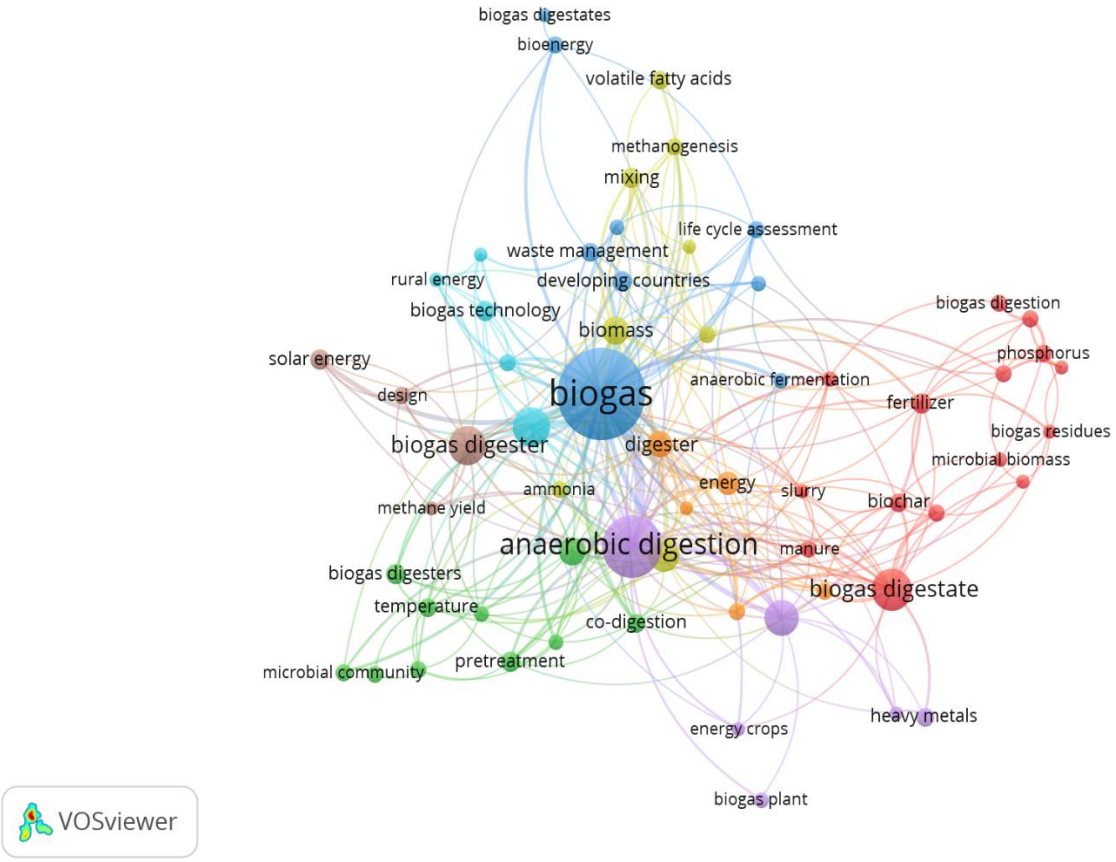

Figure 8: Co-occurrence keyword network of author's keywords

The co-occurrence network diagram generated has biogas, anaerobic digestion, biogas digestate, biomass, biogas digester, co-digestion, energy, and methane. The author's keyword 'biogas' has the highest links, total link strength, and occurrence of 45, 234, and 202, respectively (Figure 8). The other keywords are fairly represented in the diagram. The diagram further reveals a glimpse of the interest and direction of the research in the biogas technology of the extracted data. Apart from the apparent interest of researchers in biogas generation, it can be deducted from the co-occurrence network diagram that researchers have shown interest in the biological processes of the technology

represented by the keyword anaerobic digestion. The interest of researchers in the feedstock suitability of the technology is represented by 'biomass' as a keyword. Effluent use of the technology has seen attention from researchers by the co-occurrence of the keywords such as biogas digestate, manure, slurry, etc., found in its cluster. The system design of the biogas digester has received a fair research effort shown by the keywords in the biogas digester cluster. The benefits of the technology are not left out in the studies of scholars as suggested by keywords such as waste management. The co-occurrence network diagram inferences further support the authors' earlier categorization of documents. The network diagram indicates a gap in research and interest in the operation and maintenance of biogas digesters.

3.2.3 Publication characteristics of prolific journals on biogas technology

The results in Table 3 give insight into the prolific journals on biogas technology. The table highlights sources that have published a minimum of ten (10) documents with five (5) citations. Other characteristics of the sources are represented in the table to indicate the quality and impact of published works on the subject. The Scopus CiteScore and Scimago of 2020 of the respective sources of documents are presented, which suggest a good impact of research from these journals. Renewable and Sustainable Energy Reviews journal tops the list with the highest variable.

Table 3: Prolific journals characteristics

S/N	Document source	TP	TC	ACPP	CiteScore	SJR	H. Index
1	Renewable and Sustainable Energy Reviews	27	1214	44.96	30.5	3.522, Q1	295
2	Biomass and Bioenergy	23	1026	44.61	6.7	1.037, Q1	348
3	Journal of Cleaner Production	13	277	21.31	13.1	1.97, Q1	200
4	Renewable Energy	14	425	30.36	10.8	1.825, Q1	191
5	Science of the Total Environment	12	191	15.92	10.5	1.8, Q1	244
6	Bioscience Technology	27	1069	39.59	0.7	0.51, Q2	116
7	IOP Conference Series: Earth and Environmental Science	10	12	1.20	0.5	0.18, N/A	26
8	Waste Management	10	221	22.10	11.5	1.81, Q1	161
9	Advanced Materials Research	10	9	0.90	N/A	0.14, N/A	38

Note: TP = Total publication, TC = Total Citation, ACPP = average citation per publication CiteScore [71], Scimago and H index [72]

3.2.4 Number of publications from Ghanaian institutions

The contribution of academic institutions and funding agencies to the development and diffusion of technologies cannot be overemphasized. Over a thousand institutions' authors' affiliation was identified to have contributed to the data extracted. The total number of institutions in Africa that contributed at least a publication to the data extracted

was eighty-two (82) and were mostly academic institutions. These institutions published 162 documents in total, with institutions from South Africa contributing the highest. See details in appendix A. Table 4 presents the details of contributions from Ghanaian institutions.

Table 4: Individual contributions of Ghanaian institutions to biogas technology in extracted data

Country	Name of institution	Number of publication(s)
Ghana	Department of Agricultural and Biosystems Engineering, Kwame Nkrumah University of Science and Technology, Kumasi	1
	Water and Sanitation Unit, Department of Chemistry, University of Cape Coast, Cape Coast	1
	International Water Management Institute (IWMI), Accra	3
	Department Of Chemical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi	1
	Department of Civil Engineering, Kwame Nkrumah University of Science and Technology, Kumasi	1
	Department of Environmental Science, School of Biological Sciences, College of Agriculture and Natural Sciences, University of Cape Coast, Cape Coast	1
	Energy Systems Engineering Department, Koforidua Technical University, Koforidua	1
	Total	9

The potential benefits and challenges of the technology deployment requires the allocation resources for research and development to ensure the successful adoption of the technology in developing countries [25]. Ghana as a developing country with the optimistic targets set in the Renewable Energy Plan can tap in biogas technology potential. The data in Table 4 indicates the limited published studies on biogas technology which could be attributed to a lack of interest of researchers or funding support to conduct studies suitable for publication on the subject. It further highlights the inadequate resources allocated for research and development[6,73]. As shown in Table 4, except for the International Water Management Institute, the rest are academic institutions, with Kwame Nkrumah University of Science and Technology with three (3) publications representing the highest.

4. Limitation of study

Although the database used for the study captured a significant number of documents on the topic, there are inherent limitations in using a single database. Published studies that are not indexed in the Scopus database or any database would be omitted by default.

5. Conclusion

The study employed scoping review and bibliometric analysis on the Scopus database to get a bird's eye view of the scope of research conducted in the operations and maintenance of small-scale biogas digesters. Published articles were synthesized to map knowledge on methods of monitoring parameters of biogas digester operation. Network diagrams of collaborations and co-occurrence of keywords of the retrieved data were developed using the VOSviewer software. Prolific authors and journals on the subject were presented in tables to support the achievement of the study's objectives.

6. Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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8. Competing interest

The authors declare no competing interest in carrying out this study

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Appendix A: Publications by African countries

Table 6

Country	Name of institution	Number of publication
Ghana	Kwame Nkrumah University of Science and Technology	3
	University of Cape Coast	2
	International Water Management Institute (IWMI),	3
	Koforidua Technical University,	1
Tunisia	University Tunis El Manar	1
Nigeria	Ab-Olus and Associates	1
	Federal University of Technology,	1
	Federal Polytechnic Oko	1
	University of Benin	1
	University of Lagos	1
	Kwara State University	1
	College of Education Ekiadolor	1
	Federal University of Petroleum Resources	1
	Landmark University, College of Engineering,	1
	Ladoke Akintola University of Technology	2
	University of Ibadan	2
	Enugu State University and Technology	1
Botswana	University of Botswana,	2
Namibia	Desert Research Foundation of Namibia	1
	Sam Nujoma Marine and Coastal Resources Research Centre, Sam Nujoma Campus, University of Namibia	1
Tanzania	University of Dar Es Salaam	1
Egypt	Tanta University	1
	Zagazig University, Zagazig	2
	Benha University	1
	Arish University	1
	Cairo University,	2
	Menufiya University	2
	Cairo University,	2

	Suez Canal University,	2
	Soils and Water Research Institute	1
Ethiopia	Addis Ababa University,	3
	Hawassa University,	2
	Ministry Of Agriculture, Institutional Strengthening For The Forest Sector Development Program – UNDP	1
	Kotebe University College	1
	Livestock Economics Division,	1
	Department of Physics, College of Natural Sciences, Jimma Universityoromia,	1
	Mekelle University	2
	Bahir Dar Institute Of Technology, Bahir Dar University	1
Senegal	Center of Studies And Research on Renewable Energies (Cerer), Cheikh Anta Diop University	1
Cameroon	Abunde Sustainable Engineering Group, (Abundeseg)	1
	Catholic University of Cameroon,	1
	Phytobiotechnology Research Foundation	1
Morocco	Morocco, Mohammed First University	1
Rwanda	University of Rwanda	1
	Kigali Institute of Science and Technology,	1
	Development Bank of Rwanda	1
Uganda	Makerere University	11
	Greenheat	1
	Gulu University	1
	Busitema University	2
Lesotho	Technologies for Economic Development	2
Kenya	Department of Chemical and Process Engineering	1
	United Nations Environment Programme (UNEP),	1
	Mold, Egerton University	1
	Moi University,	1
	Egerton University	1

	World Agroforestry Centre (ICRAF)	3
Zimbabwe	University of Zimbabwe	1
	Bindura University Of Science Education	1
	University of Zimbabwe	1
Zambia	Copperbelt University,	1
South Africa	Agama Energy (Pty) Ltd	1
	Agricultural Research Council, Institute for Agricultural Engineering,	2
	North-West University	1
	Grain Crops, Agricultural Research Council,	1
	University of Fort Hare, Alice Campus,	20
	Arc-Institute for Soil Climate and Water, Agricultural Research Council,	2
	Centre for Environmental Management, University Of The Free State,	1
	Stellenbosch University	6
	University of Limpopo,	1
	University Of Kwazulu-Natal, Howard College Campus	7
	Department Of Agriculture, Forestry and Fisheries, Directorate: Climate Change and Disaster Management	1
	University of Johannesburg	15
	University of Cape Town,	3
	Vaal University of Technology	1
	Department of Geosciences, Nelson Mandela University	1
	University of South Africa,	2
	Department of Physics, University of Venda,	3
	Department of Rural Development and Agrarian Reform: Dohne, Stutterheim, Eastern Cape	1
	Weather/Climate and Energy Research and Applications	1
	Total	162