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Evaluating the scientific contributions of biogas technology on rural development through scientometric analysis

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ABSTRACT

The strength of rural area in pioneering technologies encountering the current challenges of biogas research has been less addressed. Scientometric analysis has been carried out to understand research trends, perspectives and promising future prospects of biogas technology in rural development. 1427 publications have been retrieved from scientific databases and analysed for major contribution of international collaborative partners, current research hotspots and subject areas to assess the evolution of biogas technology. Scientific publications on biogas grew rapidly from last decade wherein China has the highest research publications of 324 with 23.08% significant contribution. Keywords clustering analysis showed pretreatment strategies, influence of substrate mediators and its microbial interaction for process upgradation were the promising main research hotspots. The subject categories, "Energy and Fuels" is more popularized whereas "Economics" needs more attention. This study gives and insight on scientific advances and potential research gaps of biogas technology for rural development at global level.

1. Introduction

The higher amount of fossil fuel consumption leads to a negative footprint on the environment and society. To overcome this problematic system, biogas technology is used as an alternative approach for the reduction of non-renewable fossil fuel and simultaneous efficient utilization of renewable resources. The biogas is a product obtained in anaerobic conditions where biomass/substrate material gets converted into gaseous substance via a set of complex microbial communities (Khalid et al., 2019; Kumar et al., 2020).

The fundamental studies and development of microbiology in 1930 led to the identification and understanding of anaerobic microbial community for biogas research which has evolved since early-mid 17th century (Demirbas et al., 2016). The biogas technology is being promoted due to vital energy demands of the nation and their socio-economic aspects. There is huge potential in the anaerobic digestion (AD) sector and also in the constructions of the biogas plant since the calorific value of biogas is significant to generate electricity with the help of suitable generators indirectly and also as biofuel by upgrading to be used as biomethane with reduced carbondioxide (CO_2) emission (Scarlat et al.,

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2018; Mahmoodi-Eshkaftaki and Houshyar, 2020). The utilization of biomethane from AD satisfies the energy needs for aerobic-activated sludge treatment by 25%–50% after successive integration however, plant modifications may further reduce energy needs significantly (Gude, 2016). Zero negative or limited environmental side effects have been observed in adopting biogas production employing different types of green biomass (Valenti et al., 2016). The biogas generated in the anaerobic digesters or a combined heat and power (CHP) unit acts as precursor fuel to produce sustainable and renewable energy.

The favourable environmental conditions for enhancing the biogas production could be attained through maintaining efficient anaerobic conditions like stable pH, methanogenesis, enhanced nutritional balance. These conditions could be facilitated by following cost-effective methods like anaerobic co-digestion, biogas recirculation with reduced harmful emissions (Mahmoodi-Eshkaftaki and Houshyar, 2020; Singh et al., 2021). However, the studies on evaluation of different feedstocks with their mixing ratio, influence of different parameters with its inhibitory effects, diversified microbial activity, rate limiting steps, factors and the energy consumption for large scale plants are yet to be explored (Hagos et al., 2017; Vats et al., 2019). The substitutes and modification are necessary in place of conventional technologies to adapt the new trends in enhancing microbial digestibility of raw material, removing the biogas formation inhibitors, utilization of cost-effective resources and post-utilization of by-products. However, limited number of studies have been reported on the techniques involving beyond biogas technology to date. These technologies are being focused mainly to improve the process efficiency and economy in both upstream and downstream steps like design and material selection for pilot-scale plant fabrication with techno-economic, exergy based analysis (Lamidi et al., 2019; Cheng et al., 2020). These include the investigation of significance of lignocellulosic pretreatment on microbial communities (Zheng et al., 2014); composting or ensiling or micro aeration preceding to AD (Wagner et al., 2018); co-digestion using effective energy source (Khalid et al., 2019); microalgal based biogas upgradation and utilization of biosolids as soil amendment (Venegas et al., 2019; Vu et al., 2020). Utilization of real-time commercial data for the life cycle assessment of these techniques will eliminate the undermining decision-making criteria for improved process efficiency. The recent review by Patwa et al. (2020) has compared the different solid waste treatment technologies for rural area wherein the biogas technology has advantages of no pollution and less retention time compared to other methods. However, the treatment of digestate containing higher heavy metal concentration and cost associated with production and post treatment has to be addressed in such a way to make the process sustainable and affordable for rural communities. The proper understanding of current emerging techniques and research gaps in biogas technology for rural development is required to modify and design the process to be more sustainable and viable economically.

The scientometric analysis is a research technique used to determine the current trends and research gaps in the scientific field through network and domain visualization to intensify the commercialization and enhancement of knowledge (Chen and Song, 2019). The scientometric study of biogas research has been carried out by different authors but most of the studies are limited to statistical analysis rather than an in-depth understanding of research evolution and loopholes. Konur (2012) has analysed the evolution of biogas research through a scientometric approach however, the study was restricted to period up to 2012 and recent emerging techniques like employing different processing steps to make the feasible scale-up, upgradation of biogas to be used for rural application has not been discussed. Prasad et al. (2017) has discussed the recent advances in biogas research through scientometric approach whereas the evolution of research and emerging trends were not discussed with respect to cluster network.

However, to the author's knowledge, the scientific analysis of biogas research for its contribution in rural development has been seldom reported. The present study was attempted to understand scientific view of the international contribution for the production and enrichment of biogas for rural development in last decade (2010–2020). The data obtained could potentially explain the status related to current major area and inter-relationship between the international collaborate regions. Based on the scientific cluster analysis, the potential emerging trends, critical research hotspots and gaps has been illustrated. Such study would be an insight view of biogas research whether adoption of biogas technology has contributed towards the sustainable development of rural areas in global level.

2. Methodology

The scientific data has been retrieved from different sources including Scopus®, Web of Science (WoS) core collection® and Science-Direct® as it consists of indexed journals, conference proceedings and other scientific documents. The scientific algorithm-based CiteSpace ™ (5.7 R3) software was used to visualize the progressive development and cluster network analysis of treatments to interpret the research growth for the last decade in biogas technology. CiteSpace ™ (5.7 R3 version) is an open-access software based on java application, used mainly to visualize, identify and interpret the trends and outlooks of the scientific arena. It is used to respond to the queries and acquire knowledge about the dynamic structure of a scientific domain and explore the most active areas with the correlations and critical points in the cluster domain (Chen and Song, 2019). The keywords, (Rural AND ((biogas OR biofuel OR bioenergy OR biomass) OR (bioelectricity OR amendment OR microbiome OR bioeconomy OR compost))) was searched in advance mode with different combination and used for the study. The input raw data collected from web sources were converted into a unique format compatible with processing in CiteSpace ™ software. Analysis with different node types such as "countries", "author" represents the collaboration and coherence of the arena, "subject category", "keywords" determines the co-occurrence of the dynamic of the research, "cited articles" indicates the citied frequencies of documents and these analyses were carried out by setting the time slice parameters. Furthermore, the validation of the outcomes was explained via the temporal metrics such as citation burstness, centrality and silhouette value.

The scientific parameters involved in the scientometric analysis (Chen and Song, 2019) of the biogas research technology are:

2.1. Relative growth rate (RGR)

Relative growth rate (RGR) is defined as the total number of manuscripts/articles increase per unit of time. Mathematically, it can be expressed as in Eq. (1):

$$RGR = \frac{\mathrm{Log}_e^{W2} - \mathrm{Log}_e^{W1}}{T_2 - T_1} \tag{1}$$

where RGR is the mean relative growth over the particular period of time; Log_e^{W2} is the logarithm of initial number of manuscripts; Log_e^{W1} is the logarithm of the final number of manuscripts after a particular period of the interval and $T_2 - T_1$ is the difference between the initial and final years of the study period (Nirmala and Shivraj, 2016).

2.2. Citation count

Citation count is defined as total number of citation that a specific publication or journal has received over period of time, which indicate that respective publications have been cited repeatedly in order to explicit the research status relatively and also to show the similarity.

2.3. Citation burstness

Citation burstness refers to the rapid increase in the citation count of a publication in a particular period, which indicates a sudden growth can be considered as burstness of the scientific documents/articles.

2.4. Sigma

Sigma is defined as the strength of the temporal properties of the nodes, which is an indicator of scientific novelty of a publication. The higher value of sigma signifies more novelty and influence of scientific document/publication.

2.5. Average silhouette score/value

The silhouette value is an indicator of the homogeneity of clustering. The range of silhouette value is from -1 to $+1$, which defines the consistency of sub-networking or links and homogeneity of remaining cluster networks. In other words, silhouette score defines the structural metrics of similarity of certain publications to their own cluster compared with other clusters. The higher the value/score, the more will be the similarity index.

2.6. Betweenness centrality

Betweenness centrality parameter refers to the specific characteristic of any node in the network and is based on the degree of any node falling in shortest path between two nodes in the cluster network. Applicable values range from 0 to 1 indicates that higher the value of a particular node, it acts as a high impact document at the centre connecting a group of nodes and form the basis of cluster separation (Olawumi and Chan, 2018).

3. Results and discussion

From the scientific databases, total unique publication of 1427 has been retrieved using combination of keywords for last decade (2010 to 2020). It was then analysed through scientometric approach and explained with each node below. The research map obtained through scientometric analysis is based on specific scientometric parameters used for processing the data.

3.1. Distribution of publications

Numerous publications were distributed over the studied period and used for visualizing the evolution and progressive nature of the biogas arena. The graphical representation as given in Fig. 1 indicates that the number of publications in biogas research field was increasing exponentially over the period of time. Rapid growth in number of publications indicates the relative importance of field, flexibility of research, and increased attention in biogas research arena for rural development in last decade. In year 2015, 2018 and 2020, the RGR is zero which refers that there is constant or persistent number of publications in that particular year compared to previous year, whereas in year 2016 and 2019, RGR has the highest value relatively which conclude that number of publications were significantly increased as compared to previous year (Table S1).

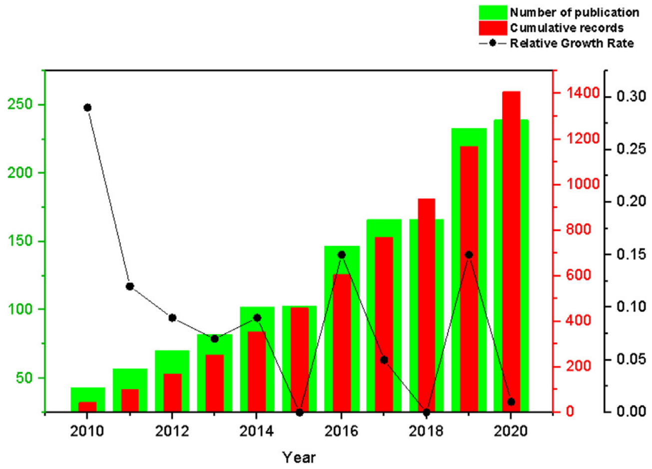

Fig. 1. Graphical representation of relative growth rate of publications on biogas technology for rural development.

3.2. Most contributing countries/region

The global research scenario in the biogas arena for rural development during the last decade (2010–2020) has been analysed through scientometric analysis. The results indicate that the biogas research field involves more than 70 countries globally. According to the cluster map obtained by CiteSpace^{TM} software, a total of 30 nodes got clustered based on the research similarity and major contribution in the biogas technology. Major key contributing nations include China, USA, India, Germany, Italy and others (Fig. 2). The larger size of the circle represents the node (country) that has higher contribution in the number of the publications related to biogas technology for rural development. China holds the first position with 324 publications and research contribution of 23.08% and then followed by the USA, India, Germany, England and Italy with the research contribution of 14.43%, 13.86%, 6.33% and 4.90% respectively (Table S2). China is ranked as a prominent nation indicating the highest number of published contributions in biogas research. About 78.03% of rural people in Wuhan, Suizhou, Huanggang provinces of China are consent enough for biogas production using livestock manure as feedstock (He et al., 2016) which also makes the country as leading contributor for biogas research in rural development. In addition, it has been reported that utilization of both digestate and biogas are equally important in terms of production of energy and in turn significantly reduce greenhouse gas emissions by recycling household and agricultural wastes (Chen et al., 2012). Recently, China has standardized the biogas production based on common household, small-scale biogas engineering and domestic sewage treatment plants, by-product utilization. It recommended for the expansion of standards in multi-aspects for adopting industry transformation and establishment of a market-based standard system for other developing countries (Wang et al., 2020a). United States of America (USA) is ranked as the foremost country in biogas research for rural development based on the centrality score of 79 and sigma value of 0.56. This indicates that the USA has more influential collaboration with other countries owing to novel research as evident from higher centrality and sigma value. Biogas technology attained societal acceptance in Brazilian culture after the demonstration of an average distance of 1.90 km m^{-3} of biomethane with 70% reduced CO_2 emissions, which is 40% efficient than conventional diesel (56% less cost-effective than diesel) (Pasqual et al., 2016). The economic evaluation of smart integrated renewable energy system utilization of solar energy aided with biogas and other renewable sources in rural areas of Chile, reported less cost thrice than extending electricity grid network (Masip et al., 2019). From the perspective of increase in number of biogas plants in different countries, their contribution for biogas research (Table S1) could be related. In global level, around 50 million micro digesters are available of which 42 million is from China, and 4.9 million from India (Iglinski et al., 2020). In most parts of India, the small scale digesters are operated on the basis of underground and non-insulated fermentation chambers which made them economical and simple structure. In USA, technologies had facilitated to manufacture anaerobic digesters with installing capacity of 977 MW whereas in India, the capacity is of 300 MW obtained using combined heat and power unit as reported by World Biogas Association (2019). The cost per unit for fabrication of biogas digester in China and India is nearly similar of 350–750 USD however, in India, very less people are consuming biogas as cooking fuel due to social non-acceptance of alternative habit and collection of sufficient feedstock from cattle (IRENA, 2017). Owing to these reasons, China and USA contribute more percentage to biogas research than India. Germany is the leader in European biogas market with 10,971 biogas units followed by 1655 biogas plants in Italy which are relatively higher than Canada which have 180 digesters with installed capacity of 196 MW. The country like Sweden is constrained with low predictability of Swedish policy and ceased demand for vehicle gas which leads to less contribution for biogas development (World Biogas Association, 2019; Iglinski et al., 2020). Based on these instances, the contribution percentage to biogas technology is varied in terms of country policies and rural welfare projects. In the

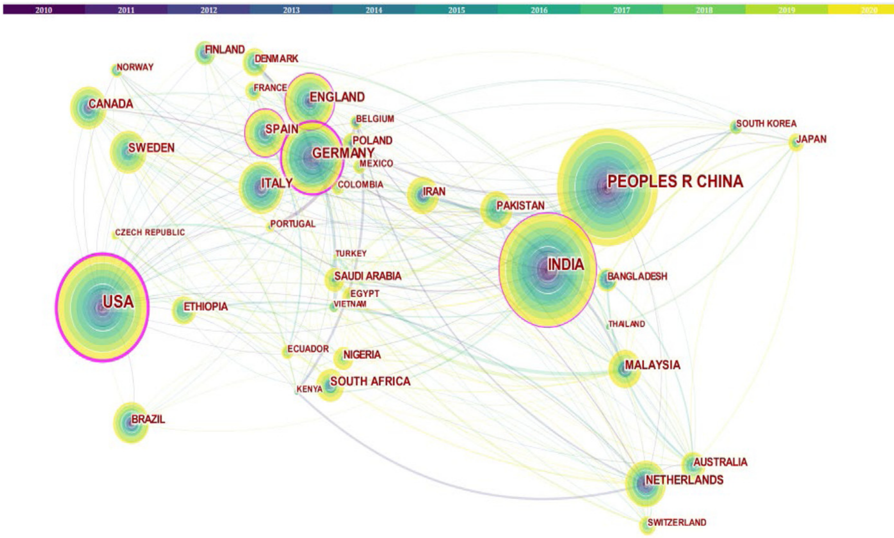

Fig. 2. Schematic representation of collaboration of global countries in biogas technology for rural development.

mid-way emerging countries such as Singapore, Vietnam has adopted agro-based industrial zero-emission system on the household level to provide a sustainable livelihood, cultivation improvement and intensification in rural farmer economy (Tran et al., 2020). In the regions of Southeast Asia-Pacific (SEAP) nations, biogas obtained from manure is found to exhibit lowest life cycle impact compared to kerosene, electricity, fuel wood, liquefied petroleum gas for its usage as sustainable household cooking fuel in remote rural communities. The scenario of using combination of different cooking fuel has been analysed in terms of life and local impact, which revealed that utilization of biogas with other local resources like fuel wood, charcoal and crop residues could be preferred that exhibits lower life cycle impacts. However, there exists a trade-off between local and life cycle impact that should be taken into account for achieving sustainable development goal scenarios of 2030 (Aberilla et al., 2020).

Among the clusters formed, cluster #0 "diesel system" is the largest cluster of countries working on biogas integrated with diesel generator for energy generation (Fig. S1). 1# "case study" is identified as the second bigger cluster with 30 members containing silhouette value of 0.625. In this cluster, the most active cited author is (Rezk et al., 2019) who has explored the constraints and opportunities of household biogas in rural China. Cluster #6 "tubular anaerobic digester" includes the node, "Brazil" where an assessment of energy potential of vinasse biogas and its economic feasibility in electricity generation was carried out. Vinasse is one of the most prominent by-products of sugar industries widely utilized as feedstock substrates in tubular biogas plants. International collaborations are being progressed with integration of biogas technology to satisfy the energy demands and utilization of outputs to make the process economically feasible and reaction engineering to remove the process constraints for improving the by-product yield and its quality.

3.3. Analysis of major contributing authors in biogas research

The cluster analysis of the node type "Author" represents the contribution of research groups on scientific publications to the biogas research arena and the outcome of the systemic analysis has been observed as shown in Fig. 3. The nodes indicate the different authors with their research groups and arranged based on the similarities in the biogas research whereas the links show their relationship among the cluster members. The larger utilized font size indicates that more contribution has been carried out by the respective author and his research team. Top ten most major contributing research groups in biogas research has been listed in Table 1. The top-ranked author based on citation count is Saini RP with a citation count of 15 however the citation burst is 2.87 bursted between 2010–2011, identified the optimized integrated renewable energy system with low cost of energy (Rs. 3.36 kWh^{-1}) involving 30% biogas for off-grid electrification to meet the electricity and cooking needs for India (Kanase-Patil et al., 2010). Chen B and his research team has more publications with a citation count of 11 and higher burst value of 5.01 belonging to 2012–2014 who has reported that the tradeoff between environmental performance and energy production could be attained by substitution for base fertilizer and seed soaking, top-dressing in digestate reuse (Chen et al., 2012). This could be considered a research hotspot owing to higher attention and citation count. Wang C's research has burst value of 2.69 appeared between 2016–2018 which could be identified as hotspot and emerging trend of biogas research, where the author has discussed about improvement in biodegradation of biomass substrate through pretreatment strategies involving duck droppings and kitchen waste in two-phase AD (Wang et al., 2017b). Among all, Wang Y has the highest centrality of 15 than other

Table 1
List of the top 10 most profile author in biogas research for rural development.

S. No	Count	Burst	Degree	Cited Year	Author
1.	15	3.92	4	2010	R P Saini
2.	11	–	15	2015	Y Wang
3.	11	5.01	4	2012	B Chen
4.	10	2.69	6	2012	C Wang
5.	9	4.08	6	2019	M Ramli
6.	7	3.17	3	2019	Mav Rad
7.	7	4.09	5	2016	E Colombo
8.	7	3.93	3	2010	M P Sharma
9.	7	3.51	1	2016	A Chauhan
10.	6	–	9	2011	Y Xu

Fig. 3. Cluster view of major contributing authors in biogas technology for rural development.

authors indicating the centre positioned node and the more vital contribution to the biogas research. The researcher group has analysed the occurrence of microbial communities in household biogas digester which reveals that community is dominated by *Clostridium, Spirochaetes, Bacteroidales* and methanogen species (Rui et al., 2015).

The cluster system is distributed based on the similarity and where the categories were labelled by means of Log-like hood ratio (LLR). The largest cluster #0 "poor area" has 19 members containing the keywords "energy policies", "sustainable development", "sustainable livelihood" (Fig. S2). The silhouette value of 0.989 (> 0.5) indicates highly significant and reasonable aggregation. The researcher and his groups in these clusters discussed the framing energy policies and sustainable techniques for improving the self-development of livelihoods of rural households. For instance, the most active citer to the cluster is Fan J, who has analysed the energy consumption characteristics of rural areas and suggested reasonable perspectives to deal energy problems. The researcher suggested to strengthen the policy support for biogas utilization to increase its contribution in energy consumption structure since the rate of usage is merely 2% for rural areas of Yan, China in total energy consumption (Fan et al., 2011). Another research group of Bluemling B presented the framework for analysing the involvement of process institutions and the social practices for biogas production and use. The analytical parameters were based on scale, supply and delivery network where the boundaries are limited to rural areas (Bluemling et al., 2013). The second cluster "techno-economic analysis" has silhouette value of 0.995 and LLR of 9.27 comprehending the efficient clustering of authors who have contributed to techno-economic and life cycle assessment of biogas. The economic benefit of biogas use will be less significant if combined heat and power is not achieved. The life cycle assessment of straw biogas showed that biogas utilization decreases the impact on environment by 50.50% in comparison to using coal as household fuel (Wang et al., 2017a). The average mean year of the authors belonging to cluster

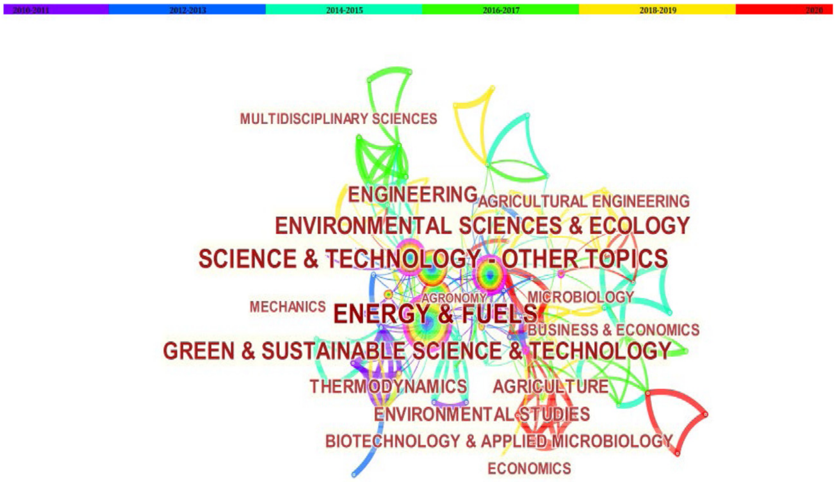

Fig. 4. Network map of influencing subject categories in biogas technology for rural development.

#0 is 2012 whereas for cluster #1 is 2017 which indicates the emerging trend is constituted by process manipulation to make it economically feasible with less environmental impacts. The key findings of the author's analysis indicate the significance of research and the need to focus on developmental strategy of biogas process for promoting rural energy and renewable agriculture.

3.4. Most published subject area

The total number of articles collected from core collection of scientific databases were analysed based on systemic algorithms for subject categories in biogas research. The network map of specific subject categories to the research field has been given in Fig. 4. The most published subject categories are "Energy & Fuels" with 474 citations that covers more than 16.59% out of the 1427 publications in biogas (Table S3). Further followed by "Science & Technology" with 330 citations covering 11.55%, "Green & Sustainable Science and Technology" having 301 citations with 10.53%, "Environmental Sciences & Ecology" with 258 citations and 9.03% contribution respectively. The subject "Energy & Fuels" acquired the highest citation value and centrality value of 0.16 which implies that the biogas research mainly emerged from energy generation perspective and spread into different categories. One of the research belonging to respective category, Prajapati et al. (2014) produced biomethane of 317.31 ± 1.9 ml g^{-1} by AD of *Chroococcus* sp. The liquid digestate resulted at the process end was utilized for algal biomass cultivation after diluting with wastewater from rural area and BG11 medium in order to close the loop of bioenergy generation. However, "Economics", "Biotechnology & Applied Microbiology" and "Engineering, Chemical" are evolutionary subjects based on centrality, indicating more focus to enhance the bioeconomy of the global nation. Recent research has explored on the optimal parameters of biogas production factors such as inoculum size (%), type of diluents and dilution ratio, to deliberate the symbiotic relationship between microbial consortia for biogas production in laboratory scale using cow manure (CM). The study was then extrapolated to field scale using low-cost tubular digester with 1:3 dilution (CM:water) for higher specific methanogenic activity produced biogas of 0.04 Nm^3 kg^{-1} of cow manure and reported the abundance of 19.8% archaeal and 80.2% bacterial microbial community (Castro et al., 2017). The mentioned instances are the key researches that have been carried out in respective subject category and resulted in growth of biogas research arena which could promote rural welfare.

3.5. Analysis of high impact articles in biogas research

The cluster outcomes of this study indicate that the most cited articles (Table 2) in biogas research arena during the last decade played a vital role in the development of biogas research for rural development. The highly cited article is "A review on Integrated Renewable Energy System based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control" (Chauhan and Saini, 2014) with the citation count of 313. In this article, Integrated Renewable Energy System (IRES) approach was made to accomplish sustainable energy demands for stand-alone applications. The mathematical model for biogas based power generation system to determine the energy consumption has been discussed where biogas and biodiesel were mixed in the ratio of 80:20 for operation of diesel engine. This prototype proposed a conversion efficiency of biogas system to 27% of electricity production with calorific value of biogas as 4700 kcal and alternatively used as cooking gas in rural areas. The second most promising cited article, "History and future of domestic biogas plants in the developing world" with the citation contribution of 273. In developing

Table 2
List of the top most cited articles in biogas research for rural development.

Rank	Title of article	Journal	Citation	Author	Discussion	References
1.	A review on Integrated Renewable Energy System based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control	Renewable and Sustainable Energy Reviews	313	Chauhan A	A prototype model was proposed a conversion efficiency of biogas system to 27% of electricity production with calorific value of biogas as 4700 kcal and alternatively used as cooking gas in rural sectors.	Chauhan and Saini (2014)
2.	History and future of domestic biogas plants in the developing world	Energy for Sustainable Development	273	Bond T	Mitigation and reduction of indoor air pollution via the biogas stoves adoption technology.	Bond (2011)
3.	Integrated renewable energy systems for off grid rural electrification of remote area	Renewable Energy	221	Kanase-patil AB	Optimization of Integrated Renewable Energy System (IRES) with 30% biogas for off-grid to fulfil the energy demands for rural electrification and cooking.	Kanase-Patil et al. (2010)
4.	Household biogas use in rural China: A study of opportunities and constraints	Renewable and Sustainable Energy Reviews	197	Chen Y	Exploration on the constraints of household biogas and its opportunities in rural field.	Chen et al. (2010)
5.	Biogas as a sustainable energy source for developing countries: Opportunities and challenges	Renewable and Sustainable Energy Reviews	187	Surendra KC	Highlight the current scenario of energy source, various socio-economic and environmental challenges, and potential barriers and emerging areas of biogas research arena.	Surendra et al. (2014)
6.	A new algorithm to characterize biodegradability of biomass during anaerobic digestion: Influence of lignin concentration on methane production potential	Bioresource Technology	171	Triolo JM	Exploration on the influence of lignin concentration of substrate on biochemical methane potential, average methane concentration 68.2%	Triolo et al. (2011b)
7	Barriers to biogas dissemination in India: A review	Energy Policy	77	Shivika Mittal	Segregation of waste, process standardization, less involvement of private players, high investment cost were identified to barriers for biogas dissemination.	Mittal et al. (2018)
8	Life-cycle energy production and emissions mitigation by comprehensive biogas–digestate utilization	Bioresource Technology	75	Chen S.	Life cycle assessment with energy and environmental was performed for the biogas plant link with agricultural and systemic greenhouse gas mitigation.	Chen et al. (2012)
9	Household energy economics in rural Ethiopia: A cost–benefit analysis of biogas energy	Renewable energy	69	Gwavuya S.	In-depth analysis of biogas or household energy system with sustainable and economic viabilities of small scale agriculture.	Gwavuya et al. (2012)
10	Techno-economic analysis of small scale biogas based polygeneration systems: Bangladesh case study	Sustainable Energy Technologies and Assessments	64	Khan EU	Techno-economic analysis and integrated biogas based polygeneration via advance technologies to meet up the rural energy demand.	Khan et al. (2014)

nations, efforts were made to reduce household air pollution relatively compared to fossil fuel burning by promoting biogas stoves and to encounter the challenges associated with domestic biogas system recently. Besides, the utilization of various feedstock such as human excreta, weeds, agricultural crop residues and kitchen waste at domestic levels were highlighted to promote opportunities towards a sustainable source of energy in rural and urban sectors. In order to improve the domestic biogas plants in the developing world and supported networks, improvisation of considerable government schemes, policies and subsidies involvement is one of the key solutions suggested by the author (Bond, 2011). Several studies have been carried out on biomethane production from lignocellulosic materials however recent

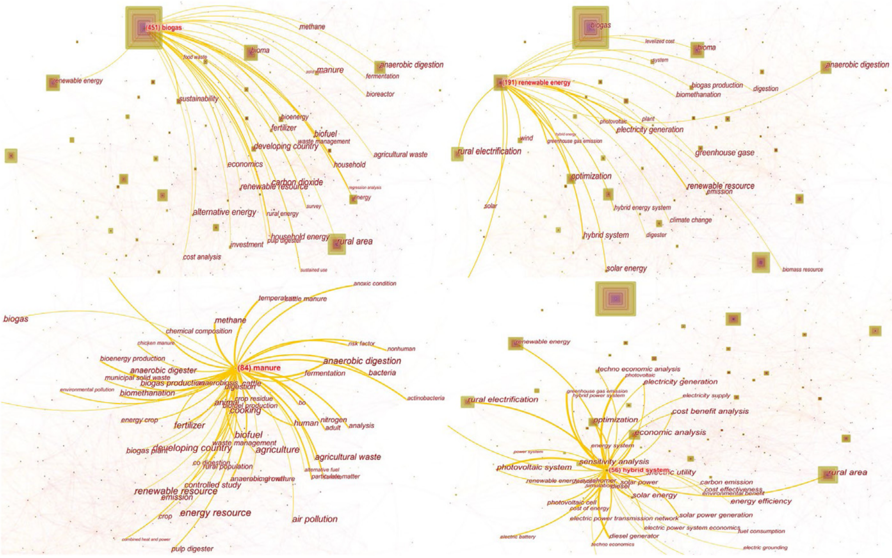

Fig. 5a. Cluster view of top four potentially evolutionary keywords in biogas technology for rural development.

studies investigated the modelling prediction of biogas yield. Biochemical methane potential (BMP) model includes the influence of fibrous fraction of biomass as an input which could be utilized for either energy crops or animal manure for predicting biogas yield and biodegradability (Triolo et al., 2011a). Techno-economic analysis and integrated biogas based polygeneration with the assistance of advanced technologies to meet up the rural energy demands were emerging rapidly. Such integrating systems are eye-catching in terms of resource utilization, feedstock availabilities and socio-economic reimbursements. In biogas based polygeneration system, excess heat generated in the gas engine could be utilized for water purification however, few potentially unexplored arena was encountered related to financial, institutional and social gaps.

3.6. Keyword analysis

The keyword cluster analysis signifies the similar arise of the composed keywords used by the authors to describe their research concept. As it can be perceived, the keywords, "biogas", "rural area", "biomass", "renewable energy" are the most prolific keywords with count 451, 232, 198, 191 respectively (Fig. 5a, Table S4). However, the keywords like "slurry" (4); "microbial community" (11); "techno-economic feasibility" (4); cost reduction (2) (Fig. 5b) has least count which indicate that the respective keywords depict the emerging research of using the digestate slurry as fertilizer, modifying the microbial community and using combined heat and power strategy to increase process efficiency with the evaluation of process feasibility (Wu et al., 2020).

From Fig. 6, it could be interpreted that during early phase of 2010, the keywords used were "anaerobic digestion", "biogas digester", "manure", "bioenergy" and "biofuel". The initial studies were focused on utilization of biomass feedstock to suitable form of bioenergy (biogas) for rural electrification. Different biomass such as lignocellulose, or livestock manure has been used for anaerobic digestion. In the mid of 2015, the keywords "pretreatment" "pulp digester", "fermentation", and "microbiome" were used. It depicts that the research was concerned towards the biodegradation; pretreatment strategic approach of the substrate feedstock/biomass to make it highly reactive for establishing biorefinery by co-utilization of bioproducts (Zhao, 2013) and managing microbiome to enhance the complex set of reactions with lower susceptibility to disturbances acquired in the anaerobic digester (Treu et al., 2016). In recent phase, the emerging keywords used are "techno-economic analysis", "microbial composition", "fuel power plant", "biomethanation", "CO_2 mitigation". It could be interpreted from these keywords that in recent research, microbial consortia have been studied through metagenomics studies with the help of advance 16S RNA/DNA sequencing to analyse diversity and characteristics of methanogenic and acidogenic bacterial niches in biogas digester. In addition, research on bio based carbon materials to be used as different types of additives and accelerants (biochar, algal char, engineered char) to reduce the operational instability, substrate bio availabilities to intensify biomethane production has been focused. The post treatment strategies of biogas through gas purification, hydrogen sulphide removal for its use in fuel power plant, and to provide efficient residential electrification through combined heat and power in rural area is being explored currently (Kasaeian et al., 2019). Thus, the keywords evolved in the timeline of research could help in understanding the evolution of research as described above. In order to emphasize more about the evolution of research, analysis of the cluster network details the progress of research from last decade. The cluster system is distributed into 7 main co-citation clusters wherein the

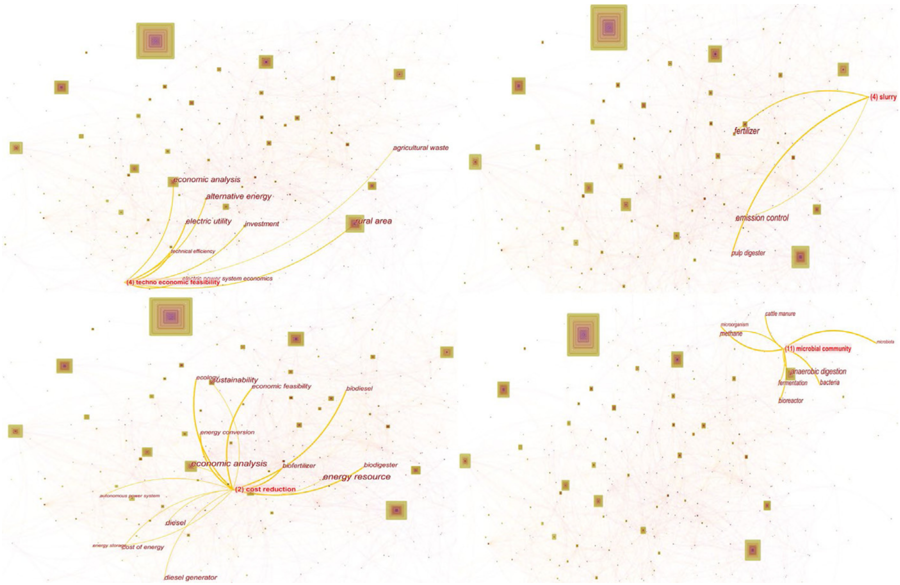

Fig. 5b. Cluster view of top four potentially emerging keywords in biogas technology for rural development.

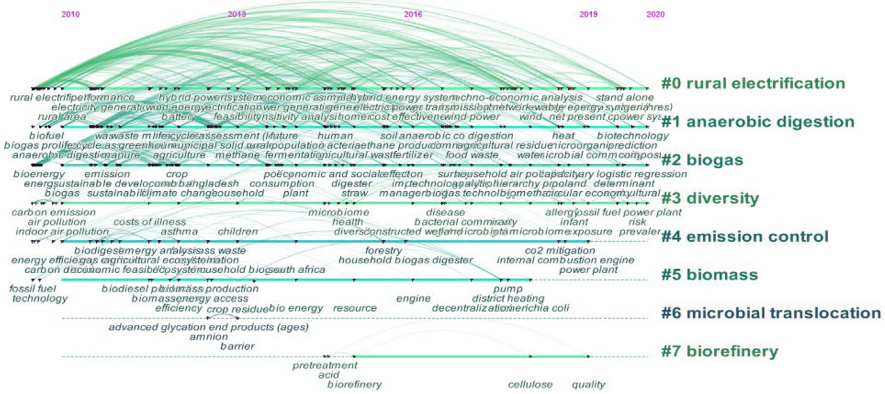

Fig. 6. Timeline view of evolution of keywords in biogas technology for rural development.

largest cluster #0 "rural electrification" has 149 members with mean year of 2014 and silhouette value of 0.829. Most of the works on biogas technology for rural development involve rural electrification since the cluster label covers the entire timeline. During 2010, the research was focused on utilization of biogas for electricity generation (identified through use of keyword, "electricity generation", "battery") whereas in recent time, the research progressed in analysing the socio-economic factor of setting up electricity grid powered using biogas (keywords like "economic analysis", "net present"). The recent emerging cluster is "biorefinery" which involve the pretreatment of feedstock to improve the performance of anaerobic digestion that produces biogas and digestate which could be used for fuel for cooking/recirculated again to digestion chamber to reduce heat energy input and fertilizer respectively. From these observations, one could understand that biogas research has evolved from focus on biogas production to techniques employed to increase the production rate and post utilization of by-products to compensate the economic investments.

4. Emerging trends and research gaps

4.1. Critical point and emerging trends in biogas research arena

The emerging trends are considered as a potential revolutionary phase of advancement in the biogas techniques and technologies assimilated in the current scientific circle. The rapid emerging of the biogas research arena occurred since 2010 period which is evident from the outcome of research in scientific literatures and this could be validated through keyword analysis. Usage of certain keywords such as "techno economic analysis", "organic waste", "fertilizer",

Table 3
List of the top 25 keywords with the strongest citation bursts in biogas research for rural development.

S. no	Keywords	Burst Strength	Begin	End	2010 – 2020
1.	Diesel generator	5.78	2010	2015	
2.	Sustainable development	4.82	2010	2013	
3.	Biofuel	4.04	2010	2013	
4.	Jatropha	3.69	2010	2013	
5.	Rural development	3.55	2010	2013	
6.	Emission reduction	3.54	2010	2015	
7.	Solid waste	3.39	2010	2011	
8.	Biomethanation	3.35	2010	2013	
9.	Environmental management	3.16	2010	2013	
10.	Biodiesel	3.10	2010	2013	
11.	Biogas digester	4.97	2012	2017	
12.	Agriculture	4.58	2012	2015	
13.	Cooking	4.45	2012	2015	
14.	Nitrogen	3.79	2012	2017	
15.	Energy crop	3.73	2012	2015	
16.	Pulp digester	4.66	2014	2017	
17.	Biomass	3.58	2014	2017	
18.	Exergy	3.36	2014	2015	
19.	Nutrient	4.2	2016	2017	
20.	Rural China	3.26	2016	2017	
21.	Constructed wetland	3.26	2016	2017	
22.	Organic waste	3.26	2016	2017	
23.	Fertilizer	3.18	2016	2017	
24.	Pretreatment	2.61	2016	2019	
25.	Techno-economic analysis	5.51	2018	2020	

and "pretreatment" with burst values of 5.51, 3.26, 3.18, 2.61 respectively as shown in Table 3, reveals the emerging trends in biogas research. The keyword, "diesel generator" has the highest burst value of 5.78 between the years 2010–2015. The low carbon content, varying composition of biogas, loss of heating value of biogas affects the sensitivity of diesel engines and increases the brake specific fuel consumption. Henceforth, the researchers explored on biogas run dual fuel based engines which increase the brake power compensating the heating value and reduces heat loss at higher loads (Sorathia and Yadav, 2012; Bora and Saha, 2015). It is also evident from country cluster analysis that dual fuel system is influential evolutionary research of biogas arena. The utilization of biogas dual fuel with higher compression ratio and injection timing improved the break thermal efficiency owing to complete combustion indicated by lower level of carbon monoxide and hydrocarbons in exhaust emissions. The liquid fuel replacement of up to 80% has been attained through dual fuel system (Ambarita, 2017). The optimization of main process parameters like compression ratio, injection time, biogas flow rate determines the effective practical utilization of biogas run dual fuel diesel engines. In this way, biogas run dual fuel diesel engines are made as significant solution for the diminution of constraints of acute power shortage especially in rural areas in India. The next emerging keyword "techno-economic analysis" having burst value of 5.51 between the year 2018–2020 involves analysing the feasibility of economic of process utilizing electricity or any other alternative energy source to produce biogas using agriculture waste in rural areas (Fig. 5b). The economic feasibility of biogas production includes several factors that integrates selection of suitable feedstock, fabrication and operation of small/household digester using locally available resources, recirculation of biogas into digester, biogas and digestate utilization for electricity/cooking and fertilizer application. The extend of techno-economic analysis to evaluate the feasibility of technology aids to improve policies for rural development in terms of economic and social dimensions of sustainability.

The keyword "pretreatment" having burst value of 2.61 between the year 2016–2019 is also one of emerging subfield of biogas research. Pretreatment strategies have been implemented in order to improve the digestion of the feedstock by changing structural integrity of biomass for improved enzymatic activity with persistent of carbohydrate levels and to remove the constraints of cost effectiveness, material loss, detoxification. The application of combined pretreatment methods like hydrothermal, alkaline, biological techniques are significantly getting attention from past few years. Use of chemical agent with hydrothermal in optimum dosage is an economic process that reduces the reaction time for methane generation. The net energy profit will be higher if scale up using unit operations that recover the heat used for pretreatment; increasing dry matter/liquid ratio in turn lower the water consumption; reducing reagent cost of alkali. This makes the anaerobic digestion process valuable in rural community in order to increase the methane yield (Xue et al., 2020). Biological pretreatment is more effective compared to physical, chemical and composting treatment owing to higher degradation rate of biochemical components, shorter retention time, low energy consumption. It has also been reported that biological pretreatment affects the structure of microbial community in less manner whereas the microbial dominance affects the methane generation. For instance, Zhao et al. (2019) stated that activity of *Methanosaeta* was predominant in biologically treated biomass and produced methane of about 62.85% after up-regulation of four key enzymes that favours the methane generation metabolic pathway, whereas its microbial activity was insignificant in untreated biomass. In order to make the process more economical and sustainable, the exploration of cheap method that does not turn down the performance of reaction system is needed. Based on this standpoint, the integration of anaerobic digestion with recycled urine (which is one of the crucial problem in terms of collection and avoidance of mixing with sewage water in rural areas) is best way of pretreatment technique that could be achieved in very short period compared to other treatment methods and suitable for rural area (Zhu et al., 2020). Thus, the cost reduction procedures utilizing the cheaper energy resource that is economically feasible and sustainable for the production of biogas and digestate slurry as biofertilizer to improve the rural area is being emerged in recent times (Fig. 5b).

Microbial consortia that influence the biogas production has been revealed with the help of the sequencing and advanced bioinformatics tools. Understanding the effect of seasonal temperature variation on microbial diversity helps in improving biogas production. For instance, the activity of methanogens will be higher during autumn however, the diversity and activity will be reduced during late winter in rural household digesters (Han et al., 2020). The upgradation of biogas could also be accomplished by reactors using mesophilic and thermophilic microbes, which is less time consuming and higher production rate (Treu et al., 2016). Microbiome fingerprinting discloses rapid evaluation and dynamic nature of particular taxa influencing biogas process. Recent studies shifted towards understanding complex microbial community existing in AD of biogas plants through the help of advanced genetic engineering techniques such as 16S rRNA amplicon sequencing analysis, metagenomics analysis.

Most of the digesters implemented in rural areas are of simple cost effective biogas digesters made using bricks, plastic composite or concrete that has been buried under the ground. In order to balance the temperature fluctuations on the yield of biogas during summer and winter seasons, a heating system and insulation is required. The upgraded biogas from the digester could be recirculated to provide enough heating however, in colder regions the power supplied through upgraded biogas and micro-gas turbine is not sufficient enough to maintain digester temperature but integration of boiler fuelled with natural gas maintains the system with sufficient heat (Baccioli et al., 2019). Although the process is beneficial in terms of biogas yield, techno-economic constraints limit its feasibility for rural areas. Pham et al. (2014) reported that there is no significant difference on yield of biogas obtained from stryofoam insulated reactor compared to non-insulated reactor under the influence of temperature fluctuations. The author further added that based on the significant relationship between temperature of slurry in mixing tank and digester temperature, an optimum time should be fixed for adding the slurry which leads to increased biogas production. Pellets made from solid digestate is suitable for complete/partial recovery of heat during winter that could be used for feasible biogas production and application (Nagy et al., 2018). Based on the financial feasibility of the rural area, an optimized design of reactor with affordable heating system using either upgraded biogas recirculation or usage of digestate pellets or using proper insulation increases the biogas production without the interference of temperature fluctuations.

In rural areas, small scale digesters seldom use upgrading techniques like purification, scrubbing owing to cost factors. Usage of cost effective packed column reactor with compressor for removing the contaminants and enriching the methane content has been carried out by Kulkarni and Ghanegaonkar (2019). Recirculation of biogas addition with $FeCl_3$ into anaerobic digester for sludge treatment is effective in biogas upgrading, conservation of phosphorous and sludge conditioning (Yuan et al., 2020). Since chemical addition also add up to production cost, utilization of biochar that absorbs CO_2 and treat digestate resulting in biogas upgradation enhances process economy to be effective. Utilization of biochar as a substrate amendment reveals its potential for mitigation of ammonia emission from livestock wastes in order to increase the yield of biomethane (Wang et al., 2020b). Process integration that will be useful for wastewater treatment as well as production of upgraded biogas and fertilizer that could be applied in electricity generation and plant growth respectively ensures the environment sustainability in rural areas.

Currently, AD based biorefineries have a remarkable potential to act as a revolutionary technology that can contribute to meet excessive energy demand. Bio based refineries are the key to unlock the potential of lignin by converting low value lignin by-product into high-value coproducts in biorefinery industries. Recent research has been proceeded towards understanding and examining the biorefinery lignin accessible for AD by removing the chemical bonds of carbohydrates components from the lignocellulosic material through wet explosion for easier enzymatic activity. The wet explosion methods enhance the bioavailability of biodegradable lignin for the intensification of methane yield in the biogas plant (Khan and Ahring, 2020).

Utilization of the nanosized based particle in AD technologies is also an emerging concept where nanoparticles influence AD performance promoting the bioavailability of biomass to the microbial consortia in the biogas plant. Biomagnetic nanoparticles were explored as biostimulant for biological activities, waste management and biogas upgrading techniques with effective adverse properties. Augmentation of AD was investigated by addition of different concentration of metallic based nanoparticles (NPs) (Fe, Cu, and Ni) as amendment/additives and observed the enhancement of digestion process, intensification of biomethane and mitigation of hydrogen sulphate (H_2S). The performance of biomagnetic nanoparticles has an auspicious route in bioenergy generation, waste management which also interact with microbes in order to enhance the adsorptive removal of the contaminants and biogas production yield. The techniques empowering the recovery and reuse of nanoparticles will make the process viable and decreases the environmental risks.

From the above entries, the emerging trends of biogas research in rural development are shown to proceed with more advancements and require further research to make the process feasible with less cost and environmental risks.

4.2. Research gaps

The scientometric cluster analysis of keywords evolution studies implicates the various potential aspects of biogas technology however certain subfields has to be focused more to improve the enhancement of bio methane production, analysing the microbial community involved, intensification of the utilization of digestate slurry. The following research gaps has been found through scientometric analysis and also validated with literatures

4.2.1. Technical research gaps

- The operational skills, practical knowledge on biogas purification technologies to be used commercially in rural areas are inadequate. Taking into account of factors like cost limitations and usage by farmers, suitable biogas upgrading technology has to be afforded based on the enviro-economic analysis. By removing CO_2 and H_2S using cost-effective technique, its utilization as pilot fuel in internal combustion engines has to be promoted which could be used by common rural people (Kulkarni and Ghanegaonkar, 2019).
- Combination of physical and chemical treatment in lab scale is not energy efficient and often decreases the quality of digestate slurry that limits it use as fertilizer. The disposal cost is also higher. The interactive effect of biological pretreatment on the structure and activity of microbial communities has to be explored. Initiation of know-how to explore the potential and economic benefits of various pretreatment source that act as energy recovery through AD in rural areas is needed. In addition, pretreatment strategies using mesophilic/thermophilic bacteria system have to be studied that would enhance the AD efficiency of cellulosic biomass and intensification of methane yield generation.
- Metagenomics analysis on the microbial consortia consisting of prominent bacteria, fungus and genetic manipulation of species that favours the metabolic pathway of methane production is needed. The interaction between changes in microbial community structure, functional gene expression, activity in AD process and methane generation has to be explored further since the link between the keyword "microbial community" and any keyword related to interactive effects, genetic could not be found in Fig. 5b (Ghosh et al., 2020).
- Environmental education about the significance, benefits and technical knowledge about agriculture waste recycling has to be promoted to enhance the rural ecological environment. Henceforth, lack of an educational program associated with biogas technologies provided to the public, private and institutional sector could be a barrier in the rural ecosystem.
- The different types of feedstock availabilities at rural sector were not much being explored to the maximum potential. The lack of physical auditing and maintenance of biogas plant and usage of alternate fuel such as liquefied petroleum gas has made the biogas plant non-functional on which serious interventions are needed.

4.2.2. Economic research gaps

- Techno-economic analysis playing a vital role in the selection of resources and operational procedures in highly sophisticated instruments that need to be installed in the rural sector is an ultimate challenge. Large scale construction of anaerobic digester, locating an apparatus (photovoltaic, micro-grid, solar PV system), higher number of technical supervisor are the negative impact on the economy of the biogas plant. In the case of biomethanation, techniques that reduce the cost for high investment processes like installation of purification unit, combined-heat power unit and gas-conducting units has to be explored since the link between keyword "techno economic feasibility" and any other keyword related to large scale/pilot level could not be found in Fig. 5b.
- Maintaining and managing the cost of the biogas plant in low income households rural sector is a huge task. The upfront installation cost, availability of feedstock, water and lack of technical skill and maintenance expertise of farmers has to be focused more in countries like Bangladesh, Bhutan, Vietnam and India to make the biogas technology feasible even for low-income farmers.
- The capital cost is one of key barrier for installing biogas plant in rural areas. The total cost for installation of biogas plant that produces 1 m^3 of biogas per day is of 348 USD which is relatively higher than average monthly expenditure of households in half of rural areas of certain countries (Mittal et al., 2018). For instance, In India, the government provides subsidy of around 32%–35% of total installation cost of family biogas plants which also could not compensate with the expenditures of low-income households in rural India. In addition, the governmental scheme such as National Biogas and Manure Management Programme (NBMMP) targets the rural people having cattle more than two and in Bhutan having a jersey cow as a criterion for availing subsidy makes difficult for majority of low-income rural

households to avail the subsidy. Also, the procedural delay in sanctioning the subsidy, physical auditing, non-revision of subsidy amount increases the overhead cost (CAGI, 2015). This act as a barrier for low-income household people to adopt biogas technology owing to lack of sufficient financial support in the form of subsidies, bank loans. The assessment of socio-economic impacts of agricultural subsidies for its effect on progress of the nation's economic status has to be extrapolated to many countries like India, Bhutan (Wang et al., 2019).

4.2.3. Environmental research gaps

- Biogas effluent sludge generated from the biogas plant consisting of abundant odour, and ammonia acts as inhibitor for the methanogenic bacteria that leads to reduction in the methane yield in the digestate. Research on treating the contaminants and inhibitor compounds existing in sludge to be utilized as fertilizer for increasing the fertility of the soil ecosystem should be emphasized since the link between keyword "slurry" and any keyword related to treatment could not be found in Fig. 5b.
- The operation of household anaerobic digesters in rural areas situated in low temperature range is difficult owing to significant fluctuations in air temperature. Insulation of digester with better characteristic materials or alternative unit process to maintain the internal temperature without biogas leakage has to be evaluated to maximize the biogas production in all seasons.
- The development of bio absorbent and bio based membranes in biogas upgrading technologies has to be explored at a high rate for the removal of impurities like H_2S, CO_2, other impurities and boost up biomethane production simultaneously (Valenti et al., 2016).

5. Future scope

Biogas is considered to be the future of renewable energy with sustainable approach, where adaptation of certain advanced techniques and technologies will progress to effective routes for production of biogas from substrate biomass. Optimization of uncertain conditions for anaerobic co-digestion owing to wide diversity of feedstock composition and its availability in rural areas will improve the process efficiency. The development of universal mathematical model that integrates the new metabolic pathway linking the structures of lignocelluloses and the manures paves the path for prediction and increasing the biogas production. The expansion for the accessibility of sufficient funds, awareness programme on maintenance with proper expertise procedure of AD operation, implementing biogas digester after careful examination of enviro-economic factors in rural areas will renovate the non-functional biogas units in countries like India, Bhutan, etc. In addition, lab scale research should be extrapolated to rural people in order to disseminate the biogas technology to rural people without any barriers. At the household level in rural sectors, the major accidental damage occurring during the handling of sophisticated equipment; poor methane production and institutional support has to be focused as major future challenges. Collaborative research would be advantageous to develop new innovative, advance technologies related to biofuel/biogas and to make optimum utilization of resources available in the respective countries. Framing of governmental policy guidelines for plant-based or agricultural biofuels, revision of existing subsidy policies, availability of potential feedstock depending upon their geographic and climatic conditions leads to sustainable development of biogas research in rural areas. Maintaining and developing a database to portray specific information on biofuel preferences among the member of global nation develops the knowledge on biogas research.

6. Conclusion

The study presented the scientometric analysis to explicit the research map of biogas arena. Biogas research has evolved from focus on biogas production to techniques employed for increasing production rate and post utilization of by-products to compensate economic investments. The biogas technology has contributed to sustainable development of rural area in developed countries whereas in developing countries, owing to improper maintenance of digester units, insufficient subsidy and governmental policies limits the development of biogas technology. Based on this perspective, significant steps are needed to renovate the non-functional biogas digesters by spreading the awareness for operational skills and knowledge, ensuring the availability of subsidy for low-income households, enables the sustainable development of biogas technology in rural areas. In a nutshell, this study helps to give an insight into the evolution of biogas research and understanding of potential research gaps that could be focused to improve the application of biogas for rural welfare.

CRediT authorship contribution statement

Stanzin Tundup: Conceptualization, Data curation, Investigation, Writing – original draft. **Mari Selvam S:** Conceptualization, Data curation, Writing – original draft. **Roshini P.S.:** Investigation, Writing – review & editing. **Arvind Kumar:** Funding acquisition, Supervision, Writing – review & editing. **Abanti Sahoo:** Funding acquisition, Supervision, Writing – review & editing. **Balasubramanian Paramasivan:** Conceptualization, Funding acquisition, Writing – review & editing, Supervision, Final approval.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2021.101879.

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