Exploring Nano technological Advances in Biogas Production from Organic Waste: A Critical Review

Pritam Kumar Dikshit, Koneru Lakshmaiah Education Foundation (KLEF), Vaddeswaram 522302, Andhra Pradesh, India

Abstract

Organic wastes, abundant in biodegradable components, emerge as a compelling solution for generating sustainable bio energy. Biogas, a product of anaerobic digestion (AD) applied to organic waste, offers a viable alternative with a calorific value ranging from 21 to 25 MJ/m3. It serves as an excellent substitute for fossil-derived fuels and natural gas, while concurrently contributing to a remarkable reduction of greenhouse gas (GHG) emissions by more than 80%. Nevertheless, it's crucial to acknowledge the challenges associated with the accumulation of ammonia during the AD process. This issue can lead to a decrease in biomass hydrolysis efficiency and methane formation, thus posing significant limitations to the industrial applicability of AD technology. Addressing these challenges is pivotal in advancing the viability of sustainable bio energy production from organic waste.

1 Introduction

The escalating demand for energy due to uncontrolled population growth, industrialization, and rising living standards has led to a heavy reliance on non-renewable energy sources like natural gas, coal, and oil. However, their usage has caused severe environmental threats, including greenhouse gas emissions, loss of biodiversity, rising sea levels, and climate change[1]. To address these challenges, there is an urgent need for sustainable and eco-friendly energy sources. Among the alternatives, biofuels, including biogas, have gained significant attention in recent years due to their potential to reduce fossil fuel consumption and associated environmental hazards. Biogas, primarily composed of methane and carbon dioxide, offers an economically viable and eco-friendly alternative energy source. Its production through anaerobic digestion (AD) of organic waste has emerged as a promising technology [2]. However, the AD process faces limitations, such as lower productivity, operational constraints, and the accumulation of ammonia, hindering its widespread adoption in industrial sectors. In recent years, nanotechnological advancements have shown promise in enhancing biogas production from organic waste. Nanoparticles, at the nanoscale (1 to 100 nm), possess unique physicochemical properties, including high surface-to-volume ratio, which enhances their catalytic activity and stability. Incorporating nanoscale materials as micronutrients in the AD process has been found to promote microbial growth, improve degradation efficiency, and increase biogas yield. This critical review article summarizes the latest reports and research on nanotechnological advancements in biogas production. It explores the impact of nanomaterials in enhancing the AD process and biohydrogen production from organic waste [3]. The review highlights the superior effects of nanoscale materials and their versatile applications in various sectors. By shedding light on the potential benefits and challenges of utilizing nanomaterials in biogas production, this review aims to contribute to the ongoing efforts towards sustainable and efficient bioenergy generation.

2 Various sources of organic waste

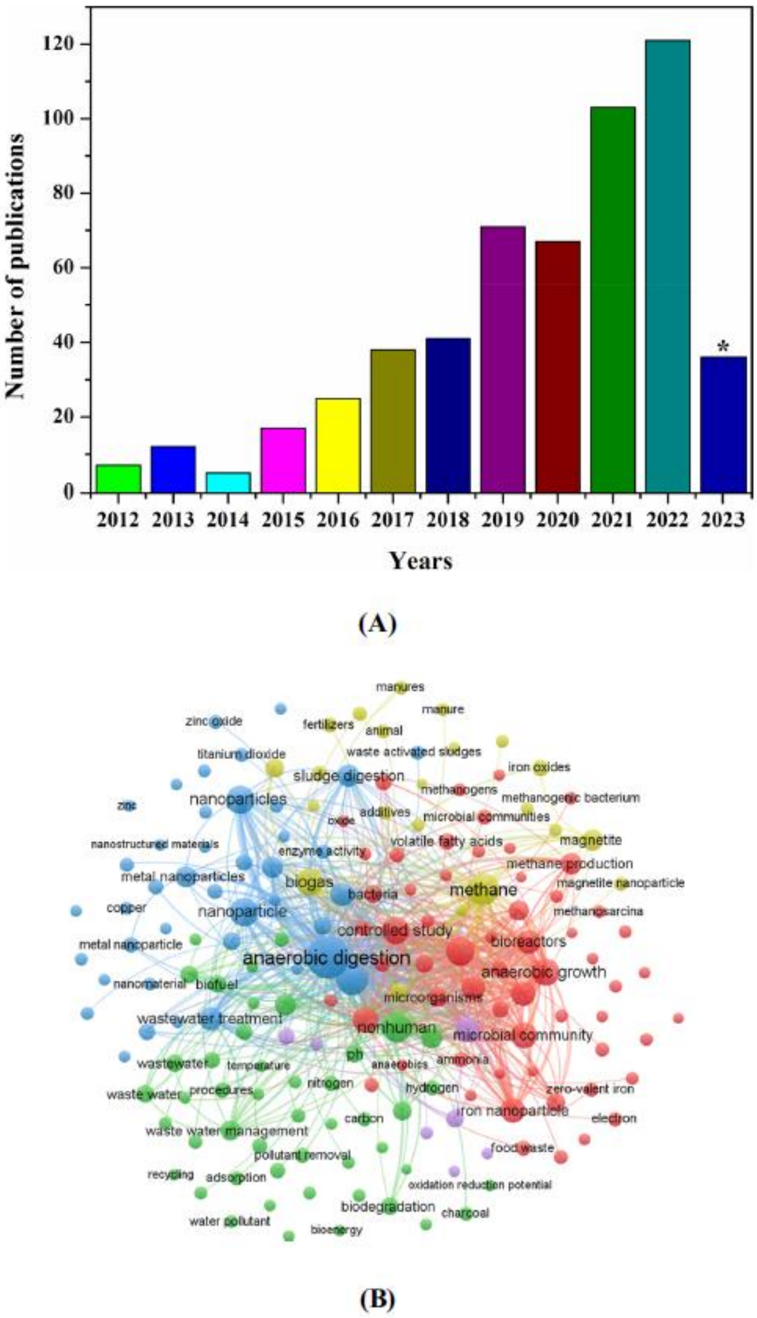

Fig. 1 **A** The number of publications with the keyword "nanoparticles" and "anaerobic digestion" in Scopus as on March 27, 2023*. **B** Network visualization of terms associated with "nanoparticles" and "anaerobic digestion" (color figure available online)

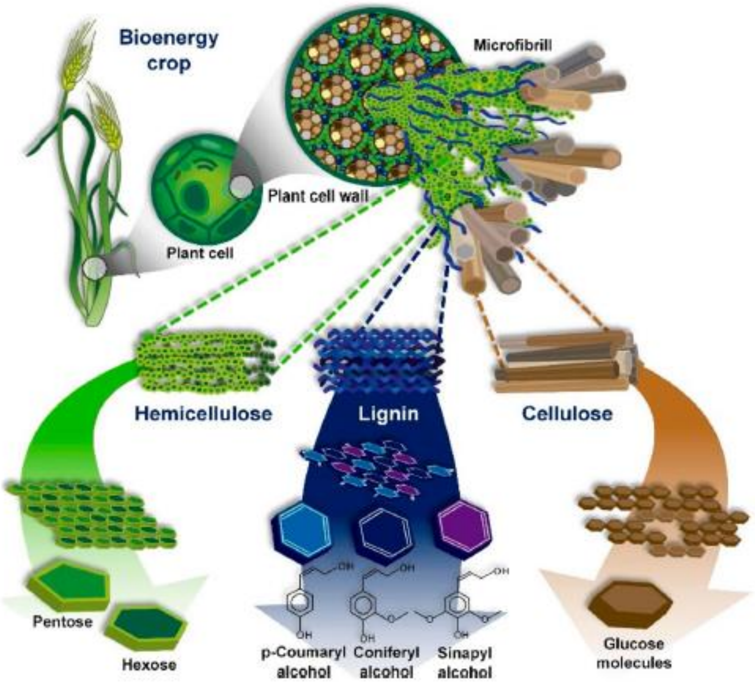

Fig. 2 Structure of lignocellulosic biomass. Adopted from Hernández–Beltrán et al. [36]

Table 1 Wastewater compositions from various sources

Source	COD (g/L)	BOD (g/L)	Total nitrogen (mg/L)	Total phosphates (mg/L)	TSS (mg/L)	VSS (mg/L)	pH	Reference
Brewery wastewater								
	2–6	–	25–80	10–50	2900–3000	–	3–12	[41]
	8–14	–	80–280	20–90	500–1300	380–1100	5.2–6.2	[42]
	22.5–32.5	–	320–450	144–216	–	800–1400	3.2–3.9	[43]
Meat processing wastewater								
Poultry	2.36–4.69	1.19–2.62	147–233	33–128	640–1213	–	6.5–7.0	[44]
Cow and swine	2–6.2	1.30–2.3	–	15–40	850–6300	–	6.3–6.6	[45]
Tapioca starch wastewater								
	8.56–8.91	5.81–6.02	–	–	1240–1695	900–1005	4.5–4.8	[46]
	10.496	6.3	525	94	827	–	4.5–4.9	[47]
	16.362	7.5	–	–	1742	1687	4.56	[48]
Ethanol wastewater								
Molasses	160.0	64.9	2638.0	907.0	11,400.0	10,400.0	4.29	[49]
Cassava	86.3	–	1755.0	21.4	48,250.0	40,800.0	4.27	[49]
Palm oil mill effluent								
	70.5	35.0	1020.0	–	26,600.0	–	4.7	[50]
	56.5	3.50	810.0	–	8300.0	–	5.1	[51]
	85.9	40.3	830.0	–	30,500.0	–	4.5	[52]

3 Nanotechnological approach for biogas production

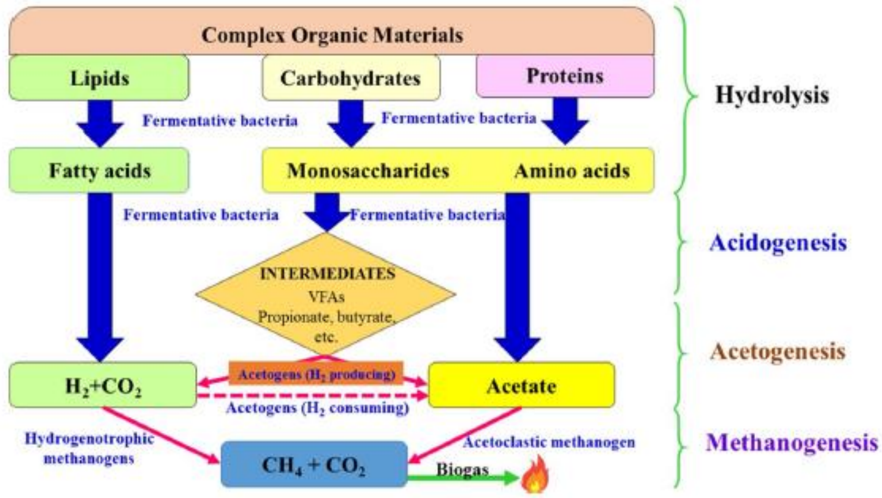

Fig. 3 Steps involved in anaerobic digestion process for the conversion of complex organic matters into biogas

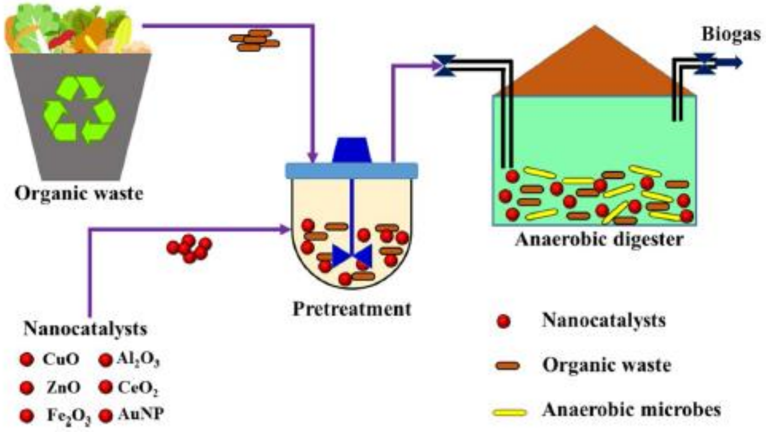

Fig. 4 Schematic of nanocatalyst mediated anaerobic digestion of organic waste for biogas production

Table 2 Application of nanoparticles in anaerobic digestion process for the production of biogas

Substrate type	Nanoparticle	Size of NP (nm)	Operating conditions	Summary	Reference
Lignocellulosic biomass					
Wheat straw	Fe_2O_3–TiO_2 and NiO–TiO_2	9.8, 11.1	Temp. – 55 °C; substrate – 0.47 g; duration – 18 days; Fe_2O_3–TiO_2 – 2.85 to 285 mg/g substrate; NiO–TiO_2 – 0.252 to 25.2 mg/g substrate	• Enhancement in soluble COD (13%) and total VFAs (67%) within first 4 days of experiments • NPs and salts enhanced methane production rate up to 21.1% and 29%, respectively	[90]
Corn straw	Nano zero-valent iron (NZVI) and biochar (BC)	50	Substrate – 17.7 g; Temp. – 35 °C; duration – 28 days;	• Combined addition of NZVI and biochar enhanced pH stability and the degradation of organic acids • The cumulative biogas production reached 151.06 mL/g VS which is 20.73% higher than the control	[91]
Wheat straw	Fe_3O_4	20–30	Temp. – 37 °C; pH – 7.0; duration – 35 days	• The effects of different charged Fe_3O_4 NPs on AD of wheat straw were studied • Negatively charged NPs had the greatest positive effects on the AD with 51.33% higher methane yield than control	[92]
Water hyacinth with cow dung	Co_3O_4	15–20	Temp. – 35 °C; pH – 7.0; duration – 50 days	• The biogas yield increased 27.2% in the co–digestion process with addition of 3 mg/L NPs • The methane yield enhanced by 43.4%	[93]
Industrial effluent/wastewater					
Liquefied organic fraction of municipal waste	TiO_2, Fe_2O_3–TiO_2, and NiO–TiO_2	8.8 (TiO_2), 11.1 (Fe_2O_3–TiO_2), and 9.8 (NiO–TiO_2)	Temp. – 54 °C; pH – 7.5	• Hydrolysis rate increased 58% increase with addition of Ni–TiO_2 nanocomposite • Increase in enzyme activity was observed • 23.5 mg/L Ni–TiO_2 nanocomposite increased methane production up to 24%	[94]
Beet sugar industrial wastewater	Iron oxide, MWCNT	20 (iron oxide); 10–20 (MWCNT)	Temp. – 36 °C; pH – 6.9	• Higher COD removal was observed for both the NPs compared to control • 12.6% and 28.9% more mL CH_4/g–VSS was observed for Iron oxide and MWCNT NPs	[95]
Low-strength wastewater	Magnetic granular activated carbon (MGAC)	10	Temp. – 35 °C	• Methane production was improved 3.6 times than control • The effluent tCOD was 43% lower than the control • The MGAC exhibited superior electro–conductivity than granular activated carbon	[96]
Cassava wastewater	TiO_2 nanoplate anatase [001] impregnated Luffa Cylindrica (LufTiO_2)	–	Temp. – 37 °C; duration – 21 days	• Addition of LufTiO_2 caused reduction in system delay and improvement in biogas production • The biogas production increased 51% with addition of LufTiO_2 on the 4th day of AD	[97]
Sugar refinery wastewater	$AlFe_2O_4$ and $MgFe_2O_4$	–	Temp. – 35 °C; duration – 21 days	• The methane yield in presence of $AlFe_2O_4$ (85.95%) and $MgFe_2O_4$ (93.96%) was significantly higher than that of control • The COD degradation increased in presence of NPs	[98]

Table 2 (continued)

Substrate type	Nanoparticle	Size of NP (nm)	Operating conditions	Summary	Reference
Dairy manure	Fe_2O_3 NPs and waste iron powder (WIP)	20–40	Temp. – 38 °C; duration – 30 days	• 1000 mg/L Fe_2O_3 NPs enhanced CH_4 yields by 21.11% with a reduction in H_2S by 53.89% • 1000 mg/L WIP improved methane yield by 56.89% • A significant reduction in H_2S was observed ranging from 45.20 to 77.24%	[106]
Cow manure	Ni–ferrite and Ni–Co–ferrite	0.31 (Ni–ferrite) and 0.57 (Ni–Co–ferrite)	Temp. – 37 °C; duration – 35 days	• Addition of Ni–Co–ferrite resulted in 33% increase in the biogas • Ni–ferrite showed 31% increase in the biogas production • Ni–Co–ferrite showed 31% increase in the biogas production	[107]
Cattle manure	Fe, Ni, and Co		Temp. – 33 °C; duration – 15 days	• The biogas production enhanced by 14.61% with addition of 30 mg/L Fe and 2 mg/L Ni NP mixture • The addition of 30 mg/L Fe, 2 mg/L, and 1 mg/L Co mixture increases the methane production by 19.30% • Further, the H_2S production decreased by 35.10% with addition of mixture of NPs	[108]
Cattle manure	SnO_2 NPs–doped mica catalyst ($MSnO_2$)	–	Temp. – 36 °C; duration – 32 days	• Deposition of SnO_2 NPs on mica surfaces improved its catalytic performance resulting higher biogas yield • The biogas and methane yield increased by 18.1% and 33%, respectively with addition of 0.03 mg/L $MSnO_2$	[109]
Cattle manure	Ni	65–114	Temp. – 33 °C; duration – 30 days	• Highest biogas production 792.0 mL/g VS achieved with addition of 4 mg/L of Ni NPs • The methane yield increased 70.46% with 2 mg/L NPs compared to control • In addition, the H_2S production decreased by 90.47%	[110]
Algal biomass					
Green microalgae *Enteromorpha*	Fe_3O_4 and Ni	100	Temp. – 37 °C; rotation – 150 rpm; duration – 170 h	• Maximum total biogas yield reached total biogas yield of 624 mL • The cumulative increase in biogas production for Fe_3O_4, Ni, Co, and MgO NPs was 28%, 26%, 9%, and 8%, respectively	[111]

e 2 (continued)

strate type	Nanoparticle	Size of NP (nm)	Operating conditions	Summary	Reference
rella pyrenoidosa	α–Fe_2O_3–NPs (IONPs)	< 50	Temp. – 37 °C; duration – 30 days	• The IONPs were supplemented with four different doses i.e. 0, 10, 20, and 30 mg/L • 25.14% rise in biogas yield and 22.4% enhanced methane content observed for 30 mg/L IONPs • A net 98.63% rise in biomethane potential was observed with 30 mg/L IONPs	[112]
rella vulgaris	Fe_3O_4	< 100 nm	Temp. – 37 °C; rotation – 130 rpm	• The hydrolysis efficiency reached 30% in presence of 10 ppm NPs • The highest biogas yield reached 595 mL/g VSin for NP-pretreated biomass	[81]

5 Factors influence the AD process

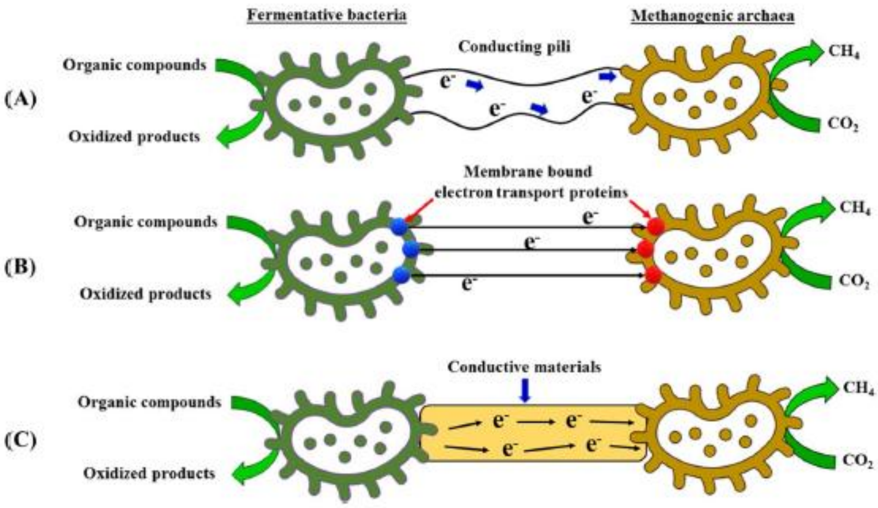

Fig. 5 Mode of direct interspecies electron transfer (DIET) between fermentative microbes and methanogenic archaea. **A** Conductive pili, **B** membrane-bound electron transport proteins, and **C** conductive materials

7 Conclusion

The previous review underlines the pivotal role that nanoparticles (NPs) with their high surface-to-volume ratio and reactivity potential play in augmenting the anaerobic digestion (AD) process for biogas production from organic waste. The inclusion of NPs leads to notable improvements in substrate hydrolysis and acidogenesis, resulting in increased formation of intermediates and higher biogas yields. The accelerated reaction kinetics attributed to NPs involve either direct or indirect interspecies electron transfer among syntrophic microorganisms. Various types of NPs have exhibited promise in enhancing biogas production, with examples including iron NPs and their compounds, carbon-based materials, and titanium dioxide.

References

1. Khalil M, Berawi MA, Heryanto R, Rizalie A (2019) Waste to energy technology: the otential of sustainable biogas production from animal waste in Indonesia. Renew Sustain Energy Rev 05:323–331
2. Ajay CM, Mohan S, Dinesha P, Rosen MA (2020) Review of impact of nanoparticle additives on anaerobic digestion and methane generation. Fuel 277:118234
3. Sathiyamoorthi E, Dikshit PK, Kumar P, Kim BS (2020) Cofermentation of agricultural and industrial waste by *Naganishia albida* for microbial lipid production in fed-batch fermentation. J Chem Technol Biotechnol 95(3):813–821