Environmental Science and Pollution Research (2024) 31:10379–10394
https://doi.org/10.1007/s11356-023-30601-w

ENERGY, ENVIRONMENT AND GREEN TECHNOLOGIES FOR THE FUTURE SUSTAINABILITY

A comprehensive review on methane's dual role: effects in climate change and potential as a carbon–neutral energy source

Murugesan Sobanaa[1] · Ragothaman Prathiviraj[1] · Joseph Selvin[1] · Munisamy Prathaban[1]

Received: 3 August 2022 / Accepted: 18 October 2023 / Published online: 26 October 2023

Abstract

The unprecedented population and anthropogenic activity rise have challenged the future look up for shifts in global temperature and climate patterns. Anthropogenic activities such as land fillings, building dams, wetlands converting to lands, combustion of biomass, deforestation, mining, and the gas and coal industries have directly or indirectly increased catastrophic methane (CH_4) emissions at an alarming rate. Methane is 25 times more potent trapping heat when compared to carbon dioxide (CO_2) in the atmosphere. A rise in atmospheric methane, on a 20-year time scale, has an impact of 80 times greater than that of CO_2. With increased population growth, waste generation is rising and is predicted to reach 6 Mt by 2025. CH_4 emitted from landfills is a significant source that accounts for 40% of overall global methane emissions. Various mitigation and emissions reduction strategies could significantly reduce the global CH_4 burden at a cost comparable to the parallel and necessary CO_2 reduction measures, reversing the CH_4 burden to pathways that achieve the goals of the Paris Agreement. CH_4 mitigation directly benefits climate change, has collateral impacts on the economy, human health, and agriculture, and considerably supports CO_2 mitigation. Utilizing the CO_2 from the environment, methanogens produce methane and lower their carbon footprint. NGOs and the general public should act on time to overcome atmospheric methane emissions by utilizing the raw source for producing carbon–neutral fuel. However, more research potential is required for green energy production and to consider investigating the untapped potential of methanogens for dependable energy generation.

Keywords Climate change · Methane emissions · Methane · Methanogen · Methanogenesis · Bioenergy

Introduction

Since 2000 BC, human civilization has progressed by using fossil fuels, where every organism sustaining is forced to depend on energy. Many generations have passed, yet the question remains "a subsequent source for energy production" (Lee and Holder 2001). Anthropogenic indulgence is the prime cause of climate change, converting wetlands into the civil area, population rise, deforestation, burning of fossil fuel, transportation, greenhouse gas emissions (GHGE), and mining (Turner et al. 2019; Kühmaier et al. 2022). Among all other issues, burning fossil fuels also (Stewart et al. 2021) has a significant negative impact on the environment by emitting 25% of greenhouse gas (GHG) and climate change (Massar et al. 2021), which is paramount to all beings and makes plant earth unfit for survival (Ejiofor 2019).

Chief gases commanding to take quick action against drastic climate changes are CO_2, CH_4, N_2O, and fluorinated gases. The present study mainly focuses on the primary greenhouse gases, CH_4 emissions rates, and concentration levels. When CO_2 is emitted into the atmosphere, 40% remains for 100 years, and 20% remains for 1000 years than other gases like CH_4 and nitrous oxide (over a century) (Global Warming Potential 2022). CH_4 is the second most significant greenhouse gas in heat-trapping in the atmosphere. The primary sources of CH_4 emissions include agriculture, waste, fossil fuels, wetlands, freshwater systems, and geological sources. Wetlands comprise 30% of the total, while agriculture, waste disposal, livestock, oil, gas, and coal mining comprise 20%. Wildfires, biomass burning, and the ocean are other culprits (Jackson et al. 2020; Rosentreter

Responsible Editor: Philippe Garrigues

✉ Munisamy Prathaban
prathaban_micro@pondiuni.ac.in

[1] Department of Microbiology, Pondicherry University, Puducherry 605014, India

et al. 2021). Likewise, boreal lakes and ponds produce two-thirds of all natural CH_4 emissions above latitude 50 North (Martin et al. 2021). By the end of the twentieth century, climatic types near the global mass of 31.3–46.3% will transition from 3.5 to 8.5 RCP (Representative Concentration Pathway) due to significant temperature rise, causing the disappearance of global climate heterogeneity (Zhang et al. 2021). In August 2020, the international team of scientists from Berkeley Lab, including William Riley (senior scientist) and Qing Zhu, estimated global CH_4 emissions had increased by nearly 5% from 2008 to 2017, which is 570 million tonnes (Global Carbon Project 2020).

However, it has been noted that CO_2 and CH_4 emissions vary with biome and physio-hydric variables of soil, temperature, vegetation, water level, and wetland salinity, which significantly impact the rates of CO_2 and CH_4 emissions (Olsson et al. 2015). Wetlands are a beneficiary source of organic carbon stores, where 15% is released into the atmosphere. About 100–231 Tg (25–40%) of CH_4 is released annually from wetland sources (Pugh et al. 2018; Li et al. 2016). Still, our role in the environment is to consider emerging global issues that could get converted into beneficial outcomes without disturbing the regular regulative cycles of the domain (Neale et al. 2021). This review highlights critical themes on CH_4 emissions, climate change, and regulatory ecology in methanogenesis, emphasizing CH_4's sustainable use in industrial and energy production for a better future.

Prime sources of CH_4 emissions

CH_4 emission from wetland

Wetlands are significant ecosystems that maintain the environment's biodiversity and regulate hydrogeographic basins (Taillardat et al. 2020). Soil is the universal habitat for most organisms, and the bio-geo cycle changes based on vegetation and soil locality (France et al. 2022). These ecosystems support endemic species diversity and contribute to CH_4 emissions through topological conditions (Ribeiro et al. 2020; Singh et al. 2018a, b). Wetlands are significant CH_4 emitters due to fluctuations in greenhouse gas efflux and changes in genera and vegetation (Baker-Blocker et al. 1977). The deep-down anoxic condition in wetlands leads to the accumulation of humic acid, creating an environment for carbon sequestration. The diverse biome from higher to lower range at each level concerning temperature variation is shown in Fig. 1. The sequestered carbon overweighs CH_4 production in non-vegetated areas (Laanbroek, 2010).

Fluctuation in organic matter affects the vegetative structure of wetlands, leading to increased CH_4 emissions with rising temperatures (Kandel et al. 2019). The water table determines the anoxic/oxic and redox boundaries, the primary cause of greenhouse gas emissions. Shallow water levels increase CH_4 emissions compared to deeper groundwater, emitting a high magnitude of N_2O (Prananto et al. 2020). An increase in CO_2 emissions was observed during the growing seasons (spring–fall) at Tibetan plateau peatlands (Cao et al. 2017; Mwagona et al. 2021). Most wetland plant roots have aerenchyma tissue that helps uptake oxygen supply and act as CH_4 conduits (Korrensalo et al. 2022). Vascular plants in natural and restored vegetation contribute to CH_4 production and consumption (Zhang et al. 2022a, b; Wilson et al. 2016; Van der Nat and Middelburg 2000).

CH_4 emissions from the dams

Dams are built to conserve water for irrigation and meet human needs, but their impacts are often debated. The uncontrolled rise in population has led to the construction of reservoirs, which can increase water consumption (Jarveoja et al. 2016). Dams also promote various activities, such as electricity generation, flood control, fish farming, fire protection, erosion prevention, and mine tail storage (Fig. 2a). There is a direct link between CH_4 eviction and accumulated organic matter in dams. The deposited organic matter involves trapping CH_4 (Fearnside and Pueyo 2012; Varis et al. 2012). Deep under the water column in the dam, due to a lack of agitation and air supply, sediment gets deposited at the bottom (Maeck et al. 2013). Therefore, it serves as a hot spot for anaerobic decomposition biological mechanisms. Thereby, CH_4 is released directly into the atmosphere and does not decrease over the dam's lifetime (Chen et al. 2011). Though it serves as green energy in its prime aspect, it later serves as a significant GHG-releasing factor that considerably impacts the environment (Fearnside and Pueyo 2012; Rooney-Varga et al. 2018).

Converted peats for human subsidence

Peatlands, covering nearly 3% of the global landmass, have become a hotspot for CO_2 emissions due to anthropogenic disturbances in Northern and Southeast Asia. Southeast Asia, including Malaysia, East Sumatra, Indonesia, and New Guinea, was once considered the largest peatland carbon pool (Lupascu et al. 2020). However, expansion for economic development has led to catastrophic fires, releasing additional carbon into the atmosphere (Xu et al. 2019). The CH_4 efflux in fire-affected peatland is higher than in intact peat (Dommain et al. 2018). In contrast, the other peatlands, covering Europe, America, and Russia, account for one-third of the global carbon soil pool. By 2015, 30% of peatland was converted for palm and acacia plantations, lowering water table levels (Jarveoja et al. 2016). Southeast Asian drained peatland generates around 380–420 Tg of CO_2 per year, while 44% of carbon emissions from industrial plantations

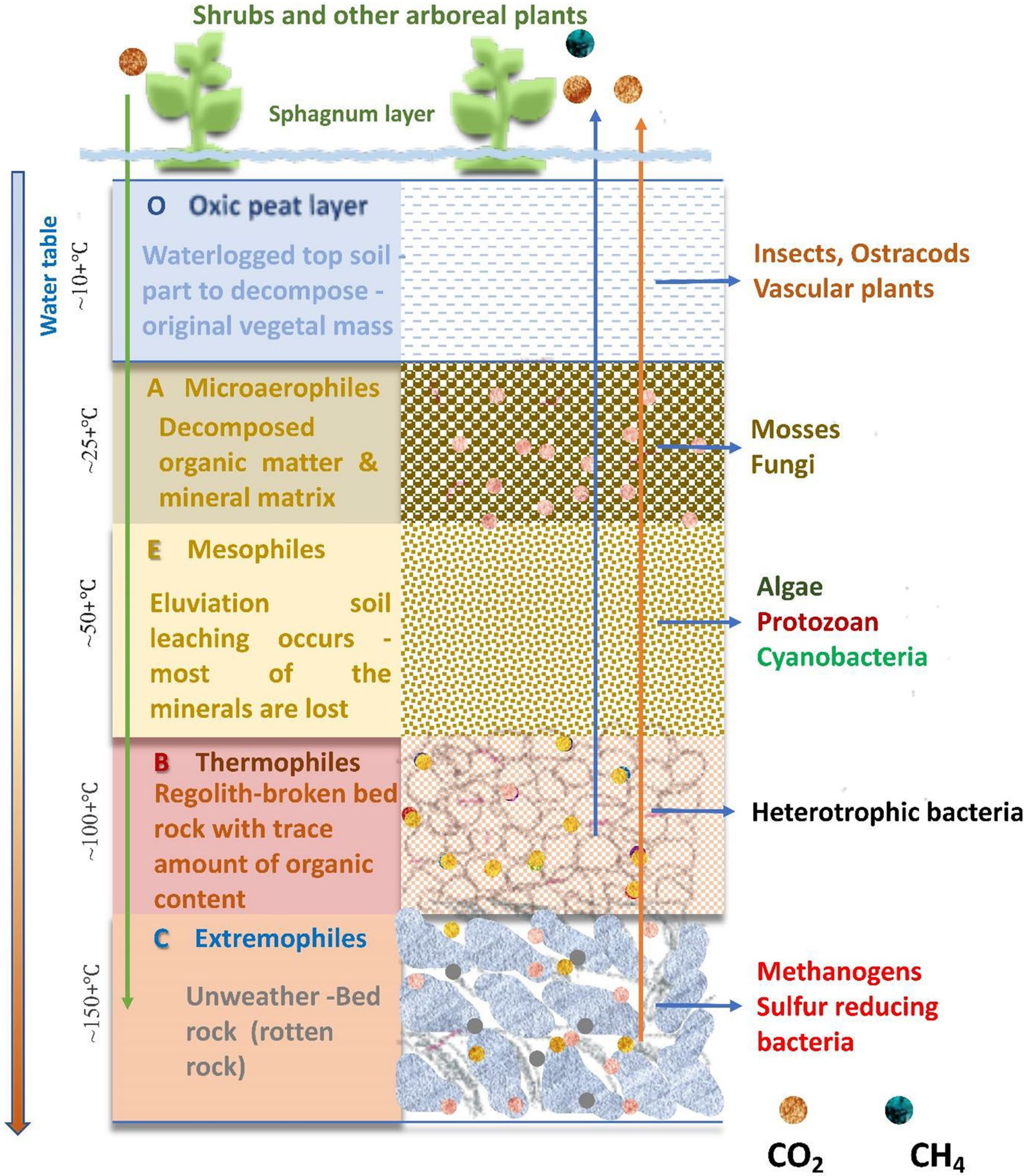


Fig. 1 Schematic representation of the interconnective and diverse biome from higher to lower range at each level concerning temperature variation (Rothschild and Mancinelli 2001)

have been reported (Miettinen et al. 2017; McCalmont et al. 2021) as depicted in Fig. 2b. The heating of peat accelerates CH_4 emissions during seasonal changes (Joabsson et al. 1999; Wilson et al. 2016).

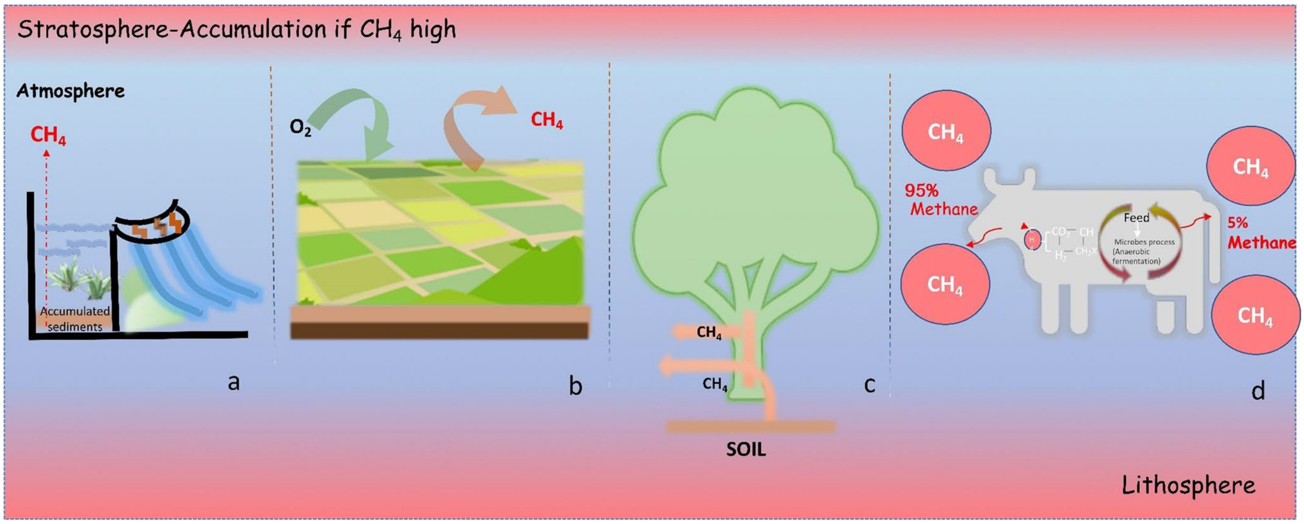


Fig. 2 Prime sources of methane emission. **a** Dam—decomposition of the accumulated organic matter at the bottom of the reservoir (Lima et al., 2008; Maeck et al. 2013; Song et al. 2018; Seo et al. 2014), **b** anaerobic condition provided by water flooded farming land (Poppe et al. 2021; Legg et al., 2015), **c** CH_4 emission from upland trees through the interaction between the tree and the soil microbiome (García-Palacios et al., 2021; Korrensalo et al. 2022; Barba et al. 2019), and **d** ruminant microbiome involving in the digestion of the carbohydrates intake (Mizrahi et al., 2018; Glasson et al. 2022)

The rise in population around South Asian countries, including China and Korea, led to the conversion of paramount peat to paddy fields, the staple diet of the significant population (Seo et al. 2014). The metamorphosis of peatland inverses its role in the environment by taking a positive side (global warming) for climate change (Ribeiro et al. 2020; Lynch et al. 2021). At the same time, draining peatlands for human settlement, cultivation, and forestry accelerated CO_2 emissions following years in the atmosphere (Krause et al. 2021; Kandel et al. 2019). However, converted peat for paddy cultivation reports 30% of annual carbon storage, referring to their tremendous impact on massive carbon sinks on the millennial scale (Ghazouani et al. 2021). Exploiting natural wetlands threatens the primary hydrological and environmental conditions (Zou et al. 2018).

According to the Fifth IPCC report, agriculture practices alone contribute 38% to global CH_4 emissions, with sub-tropical regions like South East Asia, Central and Latin America, and Africa converting most peatlands for paddy cultivation (Rahman et al. 2021; Nie et al. 2019). Improper drainage and converted peatland may evict CH_4 in a large proportion to non-paramount regions (Luta et al. 2021). India and China are the primary rice cultivators, with 2600 million people (60% Asians) relying on rice in their diet (Rahman and Yamamoto 2020). Paddy fields, covering 167.25 million hectares globally, account for about 530 Mt of CH_4 emissions annually (Ito 2015). Human activities accelerate 60% of CH_4 emissions, with 78% of CH_4 emitted globally from irrigation paddy fields (Mujiyo et al. 2017). CH_4 reacts with the rhizosphere or oxidizes in the oxic region, causing some to get trapped in soil and evicted into the atmosphere. The average mixing ratio of CH_4 in the atmosphere has increased by 6.8 ppb in the last decade. Still, the cascade releases CH_4 into the environment, causing it to linger in the atmosphere for an extended period, as per World Data Centre for Green House Gases (WDCGG) survey (World Meteorological Organization 2019).

Trees' role in CH_4 emissions

Trees play the frontier role in balancing the geo cycle in the atmosphere. Recently accelerated CH_4 emissions from trees into the atmosphere are at an alarming venue in global warming (Jeffrey et al. 2021). Intact and dead trees participate in CH_4 sequestration and eviction in the environment. An incredible amount of CH_4 gets loaded in upland trees, where more than 65% gets trapped in tree stems. CH_4 in the tree was first reported in 1970 by Bushong while cutting cottonwood trees (Flanagan et al. 2020). The heartwood of the stem accumulates 250,000 times more CH_4 than the balanced atmosphere, but the high accumulation of CH_4 in the heartwood does not relate to the total CH_4 efflux rate (Barba et al. 2019). The flux dynamic depends on internal and physical factors like species, ages, tissue type, site characteristics, and environmental conditions and primarily on stem water content controlling gas diffusion rates (Covey and Megonigal 2019), as depicted in Fig. 2c. Comparatively, CH_4 emissions from upland trees are lesser than from wetland trees. In wetlands or uplands, living trees emit more CH_4 than dead ones, regardless of the physiochemical conditions (Pitz and

Megonigal 2017). It proves tree stems are the source or sink co-related to (methanogenesis) production and CH_4 consumption (methanotrophs). CH_4 is produced deep inside the layer of soil and then released into the atmosphere through roots, stems, and leaves (Wang et al. 2017; Li et al. 2020).

Three trillion trees are present worldwide, considering the CH_4 kinetics from individual trees could upscale the overall global flux (Barba et al. 2019). The tree stem embellishes 1–6% of accumulated CH_4 in the soil, changing the upland sink into a source of efflux. Thus, the flux between upland and tree stem makes it difficult to maintain the forest temperature uniform (Pitz and Megonigal 2017). In addition, diseases like fungal infection in plants generate a CO_2 environment favouring the growth of anaerobic organisms (minor redox condition), selecting the methanogens survival. Epiphytes such as algae, lichen, bryophytes, and cyanobacteria in the tree bark help maintain the tree stem's CH_4 emissions (Lenhart et al. 2015). The consequence of regulative factors involved in climate change and global warming must be concerned to understand the bio-geo cycle flux.

Ruminants' role in CH_4 emissions

As other sources contribute to CH_4 emissions, anthropogenic is no less equal (Misiukiewicz et al. 2021; Sharma and Sinha 2013). Due to the increasing population, the need for meat and meat products will rise to 70–78% by 2050 (Min et al. 2020; Tseten et al. 2022). The rumen ecosystem plays a 90% function in digesting complex plant materials. The feed degradation and release of CH_4 from ruminants are considered a vast complex biome interaction globally (Mizrahi and Jami 2018). Among other products, CH_4 is produced at a comparable rate in ruminants (95%) and nonruminants (5%) by digestion (Zhao and Zhao 2021). The anaerobic digestion of carbohydrates in ruminants' gastrointestinal tracts produces CH_4 as they are being digested (Lan and Yang 2019), as picturized in Fig. 2d. These anaerobic archaeal methanogens convert the single carbon source to CH_4 using a straightforward oxidation process.

Ruminants undertake three modes of the process such as (i) CO_2-H_2 conversion, (ii) transformation of fatty acid chains like acetic acid, formic acid, and butyric acid, and (iii) synthesis of compounds like methanol and ethanol for degrading the feed (Lan and Yang 2019). Most methanogens undergo (a primary pathway) to reduce CO_2 to CH_4 in the rumen. Ruminant CH_4 release accounts for about 19% of global CH_4 emissions (Sun et al. 2021). The industry's continued growth, the cost of mitigation, the difficulty of implementing mitigation measures for grazing ruminants, the inconsistent effects on animal performance, and the scarcity of data on animal health, reproduction, product quality, cost–benefit, safety, and consumer acceptance are significant obstacles to reducing global enteric CH_4 emissions from ruminants (Beauchemin et al. 2020).

Anthropogenic factors adding to CH_4 emissions

Anthropocene-humans' inference in the environment leads to potential global warming (PGW), with unhealthy events like burning fossil fuels and deforestation accelerating greenhouse gas (GHG) emissions (Feng et al. 2022). GHGs disrupt the Earth's carbon cycle, including water vapour, CO_2, CH_4, N_2O, and radiative fluxes. Since industrialization began in 1900, GHG emissions have increased over time (Ritchie et al. 2020a, b). NASA warns that clearing forest areas has significantly impacted climate change. Human-caused sources of CH_4 emissions include agriculture, livestock, fossil fuel extraction, energy generation, coal mining, biogas and oil frameworks, waste treatment, and disposal (Zheng et al. 2021; Kulkarni et al. 2022). As the population grows, there is a growing demand for food, such as rice and ruminant livestock, which directly contribute to CH_4 emissions (Jorgenson and Birkholz 2010). In 2020, up to 60% of CH_4 emissions from these sources were recorded in the atmosphere (Staniaszek et al. 2022).

CH_4 emissions from oil and gas production and transportation significantly contribute to climate change. Wells leaking CH_4 can increase the risk of explosions, pollute groundwater, alter air quality, and release harmful aromatic compounds like benzene and toluene, which harm human health (Lebel et al. 2020). In Canada and the USA, CH_4 emissions from abandoned wells account for 150 times, and 20% of world emissions were reported by Williams et al. (2021). In 2022, 43% of CH_4 emissions were due to anthropogenic activity. China has risen to third place in energy consumption since 2013, consuming 8.3% more natural gas than in 2000 (Wang et al. 2022). If CH_4 leaks into the atmosphere, it has the same greenhouse gas effects as CO_2 molecules, a drawback of biogas production (Torres-Sebastián et al. 2021). Pieprzyk and Hilje (2018) predicted that global CH_4 emissions from the oil industry in 2015 would reach 22 to 59 Mt, with crude oil CH_4 emissions rising from 18 to 59% by 2040. They calculated those global emissions from venting (52%), incomplete combustion during flaring (1.4%), and fugitive emissions (42%) from diesel and petrol ranged from 8.78 to 14.80 g CO_2eq MJ-1 to 8.88 to 16.34 g CO_2eq MJ-1 in 2040. However, recent inventory estimates do not account for frequent escapes of substantial amounts of CH_4 during maintenance operations or equipment failures. Upstream production processes are the leading causes of oil and gas CH_4 emissions.

Landfills release more CH_4 into the atmosphere than previously thought, ranking third, followed by oil and biogas systems and agriculture (Singh et al. 2018a, b; Nguyen and Lee 2021). These emissions were mainly generated through microorganisms' anaerobic breakdown of organic matter (Dang et al. 2023). The two significant greenhouse gases landfills release are CH_4, CO_2, N_2O, carbon monoxide, and hydrochlorofluorocarbons (CFCs, HCFCs, and HFCs) are trace components that make up essential greenhouse gases. CH_4 burns to produce greenhouse gases like CO_2, water vapour, and ozone and filters outgoing radiation. Landfilling gas emissions contribute 50–99% to global warming, ozone depletion, and smog impacts (Wang et al. 2021a, b). According to a recent analysis by the International Energy Agency, China, India, and Russia are the world's largest CH_4 polluters (Manheim et al. 2021).

Additionally, despite the transition to clean energy, coal plays a crucial role in the world economy (Warmuzinski 2008). Coalification converts biomass into coal through biological and geological processes, releasing CH_4 gas and coal. When pressure within coalbeds is lowered due to faulting, natural erosion, or mining, CH_4 is released (Dutka and Godyń 2021; Li et al. 2022). Commercial extraction of coalbed CH_4 (CBM) has been ongoing for over 60 years (Wang et al. 2021a, b). Mine gas emissions from coal mines contribute 7% of global CH_4 production but can also come from thermogenic and biogenic sources (Beckmann et al. 2011; Kholod et al. 2020). It also contributes to the depletion of the ozone layer and has a positive ecological impact by enhancing warming. CH_4 from coal extraction can be used for electricity or commercial purposes (Ianc et al. 2020; Yang et al. 2021). However, CH_4 concentrations increased 2.5 times from 731 ppb in 1750 to 1890 ppb in 2020 (Nisbet et al. 2019).

Development towards destruction

Over the years, Earth's climate has been estimated based on physical, chemical, and biological complex ocean, land, and atmosphere processes. The radiative property of the atmosphere, a significant climate-changing factor, is strongly affected by the Earth's surface biophysical state and trace constituents, which act as an amphipathic radiative energy response (Specht et al. 2016). In addition, it is supported by atmospheric changes through anthropogenic emissions of GHGs like CO_2, CH_4, and N_2O and aerosols and volcanic eruptions (Menon et al. 2007; Xie et al. 2016). However, the mean annual increase of CO_2 is 2.40 ppm and CH_4 is 8.0 ppm per year. As per the 2021 IEA record, among other countries, India releases about 16% CH_4 from the energy sector and 8.9% (31842 kt) of total emissions (International Energy Outlook, Global Methane Tracker 2022).

CH_4 has a potential for global warming that is 80 times greater than CO_2 over 20 years and 34 times greater over 100 years (Wang et al. 2022). Naturally occurring global bio-geo cycle are incrementally and constantly affected by human activities. According to the WDCGG survey in 2020, the net global mean abundance of CH_4 is 1889 ± 2, an 11 ppb increase between 2019 and 2020. According to the methane emissions tracker 2022, CH_4 emissions from energy sources are about 70% more than anthropogenic sources estimate (International Energy Agency, Global Methane Tracker, 2022). The development and developing process clearly shows the effect of its destruction, which is not far. So, the CH_4 and CO_2 emissions efflux must be examined under comparative study in all wetlands to better estimate the threat source (Rousk and Bengtson 2014).

India and China account for 36% of the world population, with India covering 67% of the Asian population. The accelerating population in both countries converts natural land into reclaimed land for irrigation and conservation, becoming a leading carbon source. Irrigation lands account for about 6–7 tonnes (2.4–4.2%) of CO_2 annually in the Netherlands (Poppe et al. 2021). According to the COP26 and Paris Agreement reports, developed nations are primarily responsible for the accelerated mission; since the 1850s, the USA has been the top GHG emitter. As per the IPCC-2021 study, the total emissions of CH_4 from various sectors show a significant shift in the top-hit countries, as depicted in Fig. 3. China takes the top spot, followed by India, Indonesia, Russia, North America, Iran, and more. As a result, small groups of progressive steps will be adopted to reduce CH_4 emissions to 30% by 2030 (Global Climate Agreements: Successes and Failures 2021). According to Our World In Data (OWID) reports, in 2020, CO_2 emissions were significant in Asia and China after the twentieth century. Asia is marked as the largest emitter of CO_2, accounts about 53%, which is more than one-quarter of global emissions (Ritchie et al. 2020a, b). Compared with top CH_4-emitting countries like India, Indonesia, Russia, North America, Europe, and the USA, China recorded the highest emissions (> 50,000 MtC, 2021), as represented in (Fig. 3a; Supplementary Tables S1 and S2). At the same time, China (> 5000 MtC, 2021) and North America (> 3000 MtC, 2021) have taken the first two positions for CO_2 emissions from territorial and consumption as shown in Fig. 3b and Supplementary Table S3 (Global Carbon Project 2021; Friedlingstein et al. 2022; Drinkwater et al. 2023). From the last 5 years, data from various sectors taken for fossil fuel, coal, and oil are at the top-hit prime sources reported by Friedlingstein et al. (2020) and Zhang et al. (2022a, b), as represented in Fig. 4 and Supplementary Tables S4 and S5. The present global and historical carbon budget has shifted out of balance (− 0.788, 2020) due to fossil fuel emissions, atmospheric expansion, the ocean, land, and cement sinks (Fig. 5; Supplementary Table S6) (Global Carbon Project 2021; Friedlingstein et al. 2022).

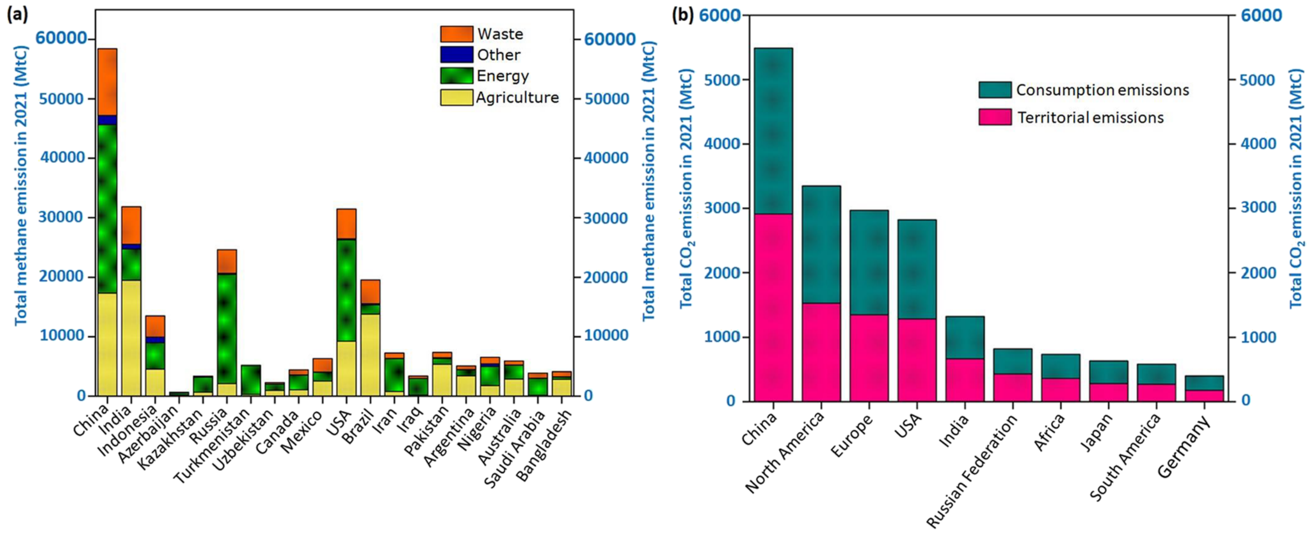
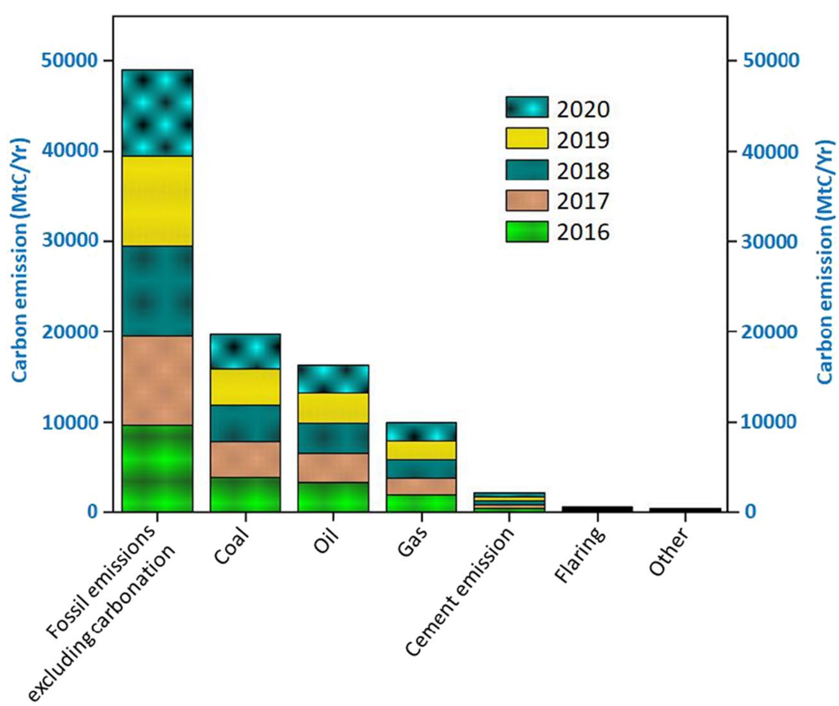


Fig. 3 Representation of the top most countries emitting methane (**a**) and carbon dioxide (**b**) measured in metric tons

Fig. 4 The last 5 years of carbon emission in various sectors were measured in MtC/year (Friedlingstein et al. 2020)



Sustainable resource

Methane is a clean, efficient biochemical and biofuel resource, but backup sources are not scientifically proven, and fossil fuels run out faster (Fan et al. 2021; Liu et al. 2021). CH_4 is an excellent fuel for combustion, and CH_4 releases less CO_2 per mole than any other fossil fuel (Lee and Holder 2001), as depicted in Fig. 6. CH_4 is a potent GHG and a more prominent energy source than other resources. Methanogenic bacteria also provide a platform for energy conversion, which can become a future CH_4-based bio-manufacture industry (Nguyen and Lee 2021). CH_4 produces ammonia, syngas, hydrogen, and methanol without exploiting nature (Richard et al. 2021). Gaseous biofuels reduce GHG emissions and have a high energy consumption value. CH_4 can become the principal feedstock for future single-cell protein production, revitalizing rural communities with much access to it (Pieja

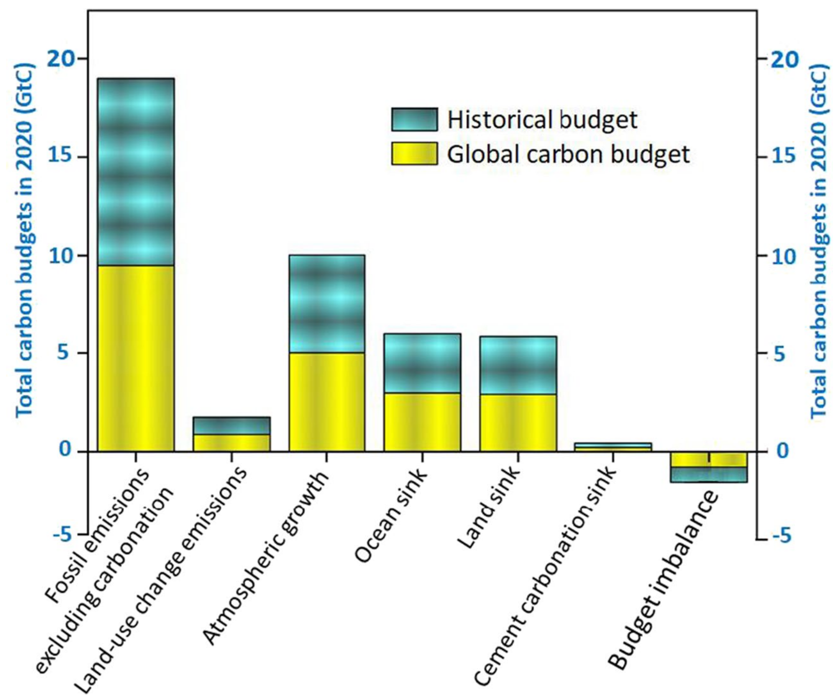


Fig. 5 Estimation of global and historical carbon budgets from the various source were measured in GtC (Global Carbon Project 2021; Friedlingstein et al. 2022)

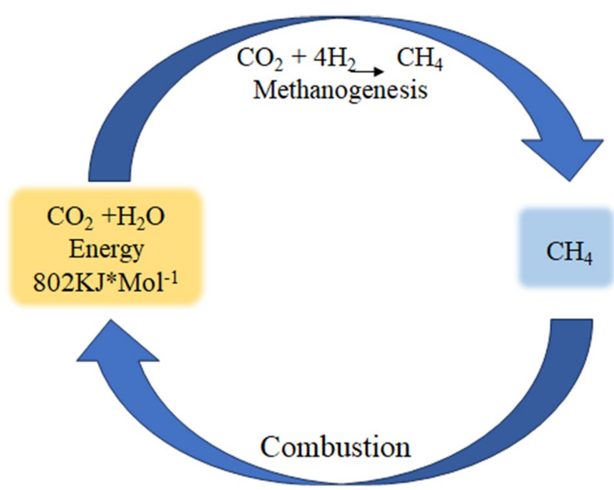


Fig. 6 Production of carbon–neutral fuel—CH_4—by CO_2-reducing methanogens

et al. 2017; Kulkarni and Ghanegaonkar 2019). We are on the brink of a radical technological revolution necessary to protect the environment and its inhabitants (Jones et al. 2022).

Biology of methanogens

Methanogens produce CH_4 to conserve high energy for adenosine triphosphate synthesis (ATPs), thereby marked as a sustainable resource for future energy development (Steinlechner and Junge 2018; Chellapandi and Prathiviraj 2020; Prathiviraj and Chellapandi 2020a; Gao and Lu 2021). It has faked the customary belief that the organism consumes energy for growth and has inspired the study area with its exotic metabolic pathways (Holmes and Smith 2016; Holmes et al. 2019). It plays a significant role in interconnective biome pathways in converting CH_4 by decomposing organic carbon dumps (anoxic/reduced condition) (Gao and Lu 2021; Dang et al. 2023). In 1776, Alessandro Volta first discovered the bio-production of CH_4 through his experiment on flammable gas from swamps and hypothesized that it is derived from decaying organic matter. Methanogens configure a significant fraction of the Earth's diversity that controls the global climate conditions (Enzmann et al. 2018). It can be isolated from extreme thermochemical gradients from acidic to alkaline (03.0–12.0 pH) conditions, psychrophilic (1 to 124 °C) to hyperthermophilic (80–98 °C) conditions, and estuaries to hypersaline. The primary spots of methanogens range from deep thermal vents to the digestive tract of animals (Chellapandi et al. 2018). Other harbour methanogen conditions include freshwater estuaries, peat bogs, swamps, and wetlands (Wolfe 1993).

Methanogens are phylogenetically and biochemically distinct organisms that preserve energy through the Wolfe cycle, producing CH_4 as a byproduct of their fundamental demand (Buan 2018). The methanogens are classified into the phyla Euarachaeota and are considered the "thermodynamic edge of life." Methanogens grow autotrophically in sealed glass vials without light, using an inorganic substrate as the sole carbon source. Intermediatory derivatives from methanogens support and create a favourable interconnective biome community (Wang and Lee 2021). Methanogens were distinguished from bacteria and archaea branches with non-methanogenic halophiles, thermoacidophiles, and hyperthermophilic archaea (Prathiviraj and Chellapandi 2020b). The enzyme system, an ancestral feature of archaea and bacteria, has been lost in all but a few lineages of prokaryotes (Juottonen et al. 2006).

The catabolic mechanism divided methanogens into CO_2-reducing, methylotrophic, and acetoclastic (Galagan et al. 2002; Juottonen et al. 2005; Prathaban et al. 2017). They need H_2 as the sole source of converting CO_2 to CH_4, where H_2 is a commonly released byproduct from other bacteria. As an essential extracellular intermediate, H_2 never accumulates as it gets rapidly utilized by other metabolic functions (Ferry 1993). Recently, the phyla affiliating seven orders have been recognized where Methanobacteriale, Methanococcales, Methanomicrobiales, Methanosarcinales, Methanopyrales, Methaenocellales, and Methanomasiliicoccales (obligate methyl-respiring methanogens) in Thermoplasmata (Xu et al. 2021). In terms of their physiology, hydrogenotrophic methanogens evolved 3.5 billion years ago. In contrast, acetoclastic and methylotrophic originated recently, before 200–450 million years but could have lost their CH_4-producing ability (Miller et al. 1988; Rohlin and Gunsalus 2010; Adam et al. 2017).

Extraordinary biome interaction

With rapid evolution and extensive adaptative physiology, methanogens seize multiple metabolic pathways. Methanogens are critical in maintaining the geothermal and global energy cycle via methanogenesis. Methanogens produce CH_4 using simple substrates such as CO_2 and H_2 via an anaerobic path (Lyu and Whitman 2019; Chellapandi and Prathiviraj 2020; Prathaban et al. 2017). Methanogens carry out methanogenesis in both forward (hydrogenotrophic) and reversed (methylotrophic) manners as they contain all the genes and enzymes within (Timmers et al. 2017; Prathaban et al. 2017). They maintain the direct interactive electron transfer (DIET) connection with exoelectrogenic organisms concerning their habitat (Mand and Metcalf 2019; Prathiviraj et al. 2019; Prathiviraj and Chellapandi 2019, 2020b). Therefore, indigenous multi-community biome and external environmental conditions determine CH_4 fluxes (Costa and Leigh 2010). The CH_4 cycle is strongly affected by climate change, both by direct means (abiotic—temperature, humid condition of the soil) and indirectly through the change in vegetation (biotic—microbiome) because they are interconnected in regulating the cycle according to the requirement (Korrensalo et al. 2022) as depicted in Fig. 7. Anaerobic digestion of organic matter occurs via hydrolysis, acidification, acetogenesis, and methanogenesis (Seemann and Thunman 2019; Xu et al. 2021). Each process occurs balanced, thereby preventing the accumulation of metabolite

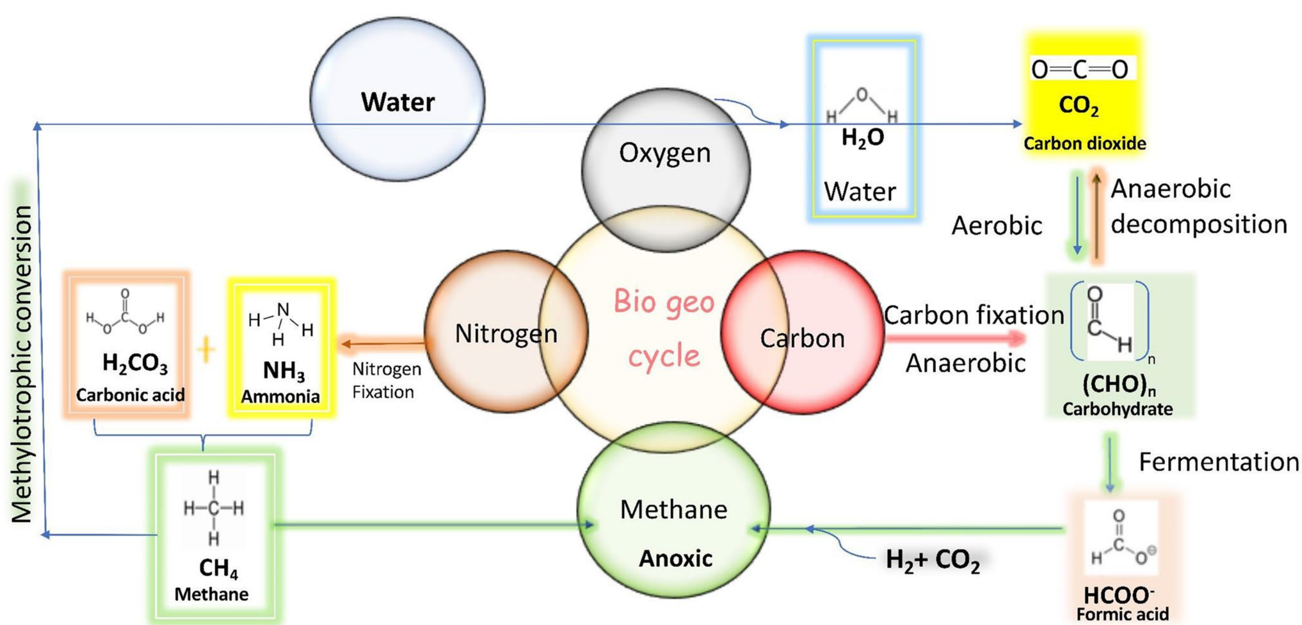


Fig. 7 Diverse microbiome interaction among the oxic and anoxic communities to maintain the biogeochemical cycle (Gao and Lu 2021; Wang and Lee 2021; Korrensalo et al. 2022)

intermediating in the system. Temperature and pH may affect the methanogenesis and the pathway of abundance in the biome community (Dhaked et al. 2010). Methanogenesis is an interconnected pathway with carbon–nitrogen cycles concerning their habitat biome (Park et al. 2018).

Conclusion and future perspectives

The increasing population and development in developing countries have significantly impacted the environment, accumulating greenhouse gas (GHG) and causing global climate imbalance. The global bio-geo sector produces 1.2 Gt of CO_2 annually, and the UN's climate report, "Now or Never," aims to limit global warming to 1.5 ℃ (Richard et al. 2021). The atmospheric CH_4 load is rising, contradicting the 2015 Paris Agreement targets of the UN Framework Convention on Climate Change (Nisbet et al. 2020). It is also described in the latest report from IPCC as "a litany of broken climate promises," revealing a "yawning gap between climate pledges and reality" (UN News report, Global perspective Human stories 2022) and also added that investing in climate-chocking industries. The G7 Leaders Declaration from May 2016 to "recognize the importance of mitigating emissions of short-lived climate pollutants" also supports a variety of existing strategies (Saunois et al. 2016).

According to IEA greenhouse gas emissions from energy, the industry was the largest sector for about 40% of global emissions in 2019 (International Energy Agency, Greenhouse Gas Emissions from Energy: Overview, 2021). For the past five decades, there has been a clear need in various sectors for a sustainable transition source of energy production. The world is at an alarming stage, fighting for future sustainability (Cain et al. 2021). As discussed above, many renewable, carbon–neutral sources are available, and in the past two decades, it has been proven and optimized. Enhanced technological development is needed in the sustainable bioenergy sector for future wellness. At the IEA March 2022 ministerial meeting press release, global energy leaders vow to accelerate and strengthen the clean energy transition. One of the main focuses of US and international climate policy is reducing CH_4 emissions from oil and gas installations. Leak detection and repair programs (LDAR) that rely on surveys based on optical gas imaging (OGI) are regularly used to reduce fugitive emissions or leaks (Fox et al. 2019; Kemp and Ravikumar 2021). However, swift action to cut CH_4 emissions from fossil fuel operations is the most effective strategy to minimize near-term climate change. The Paris Agreement (Birol 2023), which all 197 UNFCCC members signed or endorsed in 2018, intends to restrict global warming to 2 ℃ (Meinshausen et al. 2022; Birol 2023).

Microorganisms are abundant natural products that can be used for fuels and fine chemicals (Colin et al. 2011; Chubukov et al. 2016; Sindhu et al. 2019). A diverse substrate utilization potential in microbial strains could provide a competitive advantage in biofuel production. Anaerobic digestion can produce nearly half of the biogas's CH_4, which can be upgraded to over 90% CH_4, which has the same uses as natural gas (Mitchell et al. 2015). However, the accessibility of technical resources to reduce CH_4 emissions is unconscionable. The benefits of mitigating climate change extend beyond preventing global warming and fulfilling responsibilities and are crucial for a sustainable future.

Along with helping the environment, lowering CH_4 emissions might increase agricultural yields and human health by concurrently reducing ozone generation and opening up new business and job prospects (Methane Possible 2023). Thus, governmental organizations must participate in implementing schemes under shifting to bioenergy sources and waste-to-energy conversion (Mboowa et al. 2017; Liang et al. 2022; Bajar et al. 2021), for a better future (International Energy Agency: Ministerial Meeting 2022).

Abbreviations ATPs: Adenosine triphosphate synthesis; BM: Commercial extraction of coalbed CH_4; CH_4: Methane; CO_2: Carbon dioxide; COP: Conference of Parties; DIET: Direct interactive electron transfer; GHG: Greenhouse gases; GHGE: Greenhouse gas emissions; Gt: Gigatonnes; IEA: International Energy Agency; LDAR: Leak detection and repair programs; MtC: Metric tonnes; N_2O: Nitrous oxide; NASA: National Aeronautics and Space Administration; OGI: Optical gas imaging; ppb: Parts per billion; Tg: Teragram; Mt: Million tonnes; UNFCCC: United Nations Framework Convention on Climate Change; WDCGG: World Data Centre for Green House Gases

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-023-30601-w.

Author contribution SM and PR performed data analysis, conceptualization and a literature survey and prepared the draft manuscript. SJ and PM provided supervision, conceptualization, and approval for the final manuscript.

Funding Prathaban M is thankful to the Dr. D.S. Kothari Postdoctoral Fellowship, University Grants Commission (Ref. No.: F.4–2/2006 (BSR)/BL/20–21/0109), Govt. of India for the project grant. Sobanaa M is thankful to the Savitribai Jyotirao Phule Single Girl Child Fellowship (SJSGC), University Grants Commission (Ref.no: 202223-UGCES-22-OB-PUD-F-SJSGC-4671), Govt. of India, for the grant. Prathiviraj R is thankful to DST-Science and Engineering Research Board, New Delhi, India, under the NPDF scheme (Sanction No.: PDF/2019/002762/Dated: 23/12/2019), India.

Data availability The data used in this study were represented in the supplementary file.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Adam PS, Borrel G, Brochier-Armanet C, Gribaldo S (2017) The growing tree of archaea: new perspectives on their diversity, evolution and ecology. ISME J 11:2407–2425. https://doi.org/10.1038/ismej.2017.12254

Bajar S, Singh A, Kaushik CP, Kaushik A (2021) Suitability assessment of dumpsite soil biocover to reduce methane emission from landfills under interactive influence of nutrients. Environ Sci Pollut Res 28:1519–1532. https://doi.org/10.1007/s11356-020-10441-8

Baker-Blocker A, Donahue TM, Mancy KH (1977) Methane flux from wetlands areas. Tellus 29(3):245–250. https://doi.org/10.3402/tellusa.v29i3.11353

Barba J, Bradford MA, Brewer PE et al (2019) Methane emissions from tree stems: a new frontier in the global carbon cycle. New Phytol 222(1):18–28. https://doi.org/10.1111/nph.15582

Beauchemin KA, Ungerfeld EM, Eckard RJ, Wang M (2020) Review: Fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. Animal 14(S1):s2–s16. https://doi.org/10.1017/S1751731119003100

Beckmann S, Lueders T, Kruger M, Von Netzer F, Engelen B, Cypionka H (2011) Acetogens and acetoclastic Methanosarcinales govern methane formation in abandoned coal mines. Appl Environ Microbiol 3749–3756. https://doi.org/10.1128/AEM.02818-10

Birol F (2023) COP26 climate pledges could help limit global warming to 1.8 °C, but implementing them will be the key. IEA: International Energy Agency. France. https://policycommons.net/artifacts/1864750/cop26-climate-pledges-could-help-limit-global-warming-to-18-degc-but-implementing-them-will-be-the-key/2613073/

Buan NR (2018) Methanogens: pushing the boundaries of biology. Emerg Top Life Sci 2:629–646. https://doi.org/10.1042/ETLS20180031

Cain M, Jenkins S, Allen MR, Lynch J, Frame DJ, Macey AH, Peters GP (2021) Methane and the Paris Agreement temperature goals. Philos Trans A Math Phys Eng Sci 380(2215):20200456. https://doi.org/10.1098/rsta.2020.0456

Cao R, Xi X, Wei X, Wu X, Yang Y, Sun S (2017) The effect of water table decline on soil CO_2 emission of Zoige peatland on eastern Tibetan Plateau: a four-year in situ experimental drainage. Appl Soil Ecol 120:55–61. https://doi.org/10.1016/j.apsoil.2017.07.036

Chellapandi P, Bharathi M, Sangavai C, Prathiviraj R (2018) *Methanobacterium formicicum* as a target rumen methanogen for the development of new methane mitigation interventions-a review. Vet Anim Sci 6:86–94. https://doi.org/10.1016/j.vas.2018.09.001

Chellapandi P and Prathiviraj R (2020) *Methanothermobacter thermautotrophicus* strain ΔH as a potential microorganism for bioconversion of CO_2 to methane. J CO_2 Utilization 40:101210. https://doi.org/10.1016/j.jcou.2020.101210

Chen H, Yuan X, Chen Z, Wu Y, Liu X, Zhu D, Wu N, Zhu Q, Peng C, Li W (2011) Methane emissions from the surface of the three Gorges reservoir. J Geophys Res Atmos 116(D21):21306. https://doi.org/10.1029/2011JD016244

Chubukov V, Mukhopadhyay A, Petzold CJ, Keasling JD, Martín HG (2016) Synthetic and systems biology for microbial production of commodity chemicals. Syst Biol Appl 2:16009. https://doi.org/10.1038/npjsba.2016.9

Colin VL, Rodríguez A, Cristóbal HA (2011) The role of synthetic biology in the design of microbial cell factories for biofuel production. J Biomed Biotechnol 2011:601834. https://doi.org/10.1155/2011/601834

Costa KC, Leigh JA (2010) Metabolic versatility in methanogens. Curr Opin Biotechnol 29:70–75. https://doi.org/10.1016/j.copbio.2014.02.012

Covey KR, Megonigal JP (2019) Methane production and emissions in trees and forests. New Phytol 222(1):35–51. https://doi.org/10.1111/nph.15624

Dang Q, Zhao X, Li Y, Xi B (2023) Revisiting the biological pathway for methanogenesis in landfill from metagenomic perspective-A case study of county-level sanitary landfill of domestic waste in North China plain. Environ Res 222:115185. https://doi.org/10.1016/j.envres.2022.115185

Dhaked RK, Singh P, Singh L (2010) Biomethanation under psychrophilic conditions. Waste Manag 30(12):2490–2496. https://doi.org/10.1016/j.wasman.2010.07.015

Dommain R, Frolking S, Jeltsch-Thommes A, Joos F, Couwenberg J, Glaser PH (2018) A radiative forcing analysis of tropical peatlands before and after their conversion to agricultural plantations. Glob Chang Biol 24(11):5518–5533. https://doi.org/10.1111/gcb.14400

Drinkwater A, Palmer PI, Feng L, Arnold T, Lan X, Michel SE, Parker R, Boesch H (2023) Atmospheric data support a multi-decadal shift in the global methane budget towards natural tropical emissions. Atmos Chem Phys 23:8429–8452. https://doi.org/10.5194/acp-23-8429-2023

Dutka B, Godyń K (2021) Coalification as a process determining the methane adsorption ability of Coal seams. Arch Min Sci 66(2):181–195. https://doi.org/10.24425/ams.2021.137455

Ejiofor AO (2019) Climate change: a moral challenge for renewing the Earth, reflections on various churchs' responses on environmental crisis. JORAS-Nigerian Journal of Religion and Society 9: 97–108. https://acjol.org/index.php/joras/article/view/2044/1991

Enzmann F, Mayer F, Rother M, Holtmann D (2018) Methanogens: biochemical background and biotechnological applications. AMB Express 8(1):1. https://doi.org/10.1186/s13568-017-0531-x

Fan Z, Weng W, Zhou J, Gu D, Xiao W (2021) Catalytic decomposition of methane to produce hydrogen: a review. J Energy Chem 58:415–430. https://doi.org/10.1016/j.jechem.2020.10.049

Fearnside P, Pueyo S (2012) Greenhouse-gas emissions from tropical dams. Nature Clim Change 2:382–384. https://doi.org/10.1038/nclimate1540

Feng L, Palmer PI, Zhu S, Parker RJ, Liu Y (2022) Tropical methane emissions explain large fraction of recent changes in global atmospheric methane growth rate. Nat Commun 13(1):1378. https://doi.org/10.1038/s41467-022-28989-z

Ferry JG (1993) Methanogenesis: ecology, physiology, biochemistry & genetics. Chapman Hall Microbiol Ser (CHMBS) (1–35). ISBN: 978–1–4615–2391–8.

Flanagan LB, Nikkel DJ, Scherloski LM, Tkach RE, Smits KM, Selinger LB, Rood SB (2020) Multiple processes contribute to methane emission in a riparian cottonwood forest ecosystem. New Phytol 229:1970–1982. https://doi.org/10.1111/nph.16977

Fox TA, Barchyn TE, Risk D, Ravikumar AP, Hugenholtz CH (2019) A review of close-range and screening technologies for mitigating fugitive CH_4 emissions in upstream oil and gas. Environ Res Lett 14:053002. https://doi.org/10.1088/1748-9326/ab0cc3

France JL, Fisher RE, Lowry D et al (2022) δ13C methane source signatures from tropical wetland and rice field emissions. Phil Trans R Soc A 380:20200449. https://doi.org/10.1098/rsta.2020.0449

Friedlingstein P, O'Sullivan M, Jones MW et al (2020) Global Carbon Budget 2020. Earth Syst Sci Data 12:3269–3340. https://doi.org/10.5194/essd-12-3269-2020
Friedlingstein P, Jones MW, O'Sullivan M et al (2022) Global Carbon Budget 2021. Earth Syst Sci Data 14:1917–2005. https://doi.org/10.5194/essd-14-1917-2022
Galagan JE, Nusbaum C, Roy A et al (2002) Rohlin. Genome Res 12(4):532–542. https://doi.org/10.1101/gr.223902
Gao K, Lu Y (2021) Putative extracellular electron transfer in methanogenic archaea. Front Microbiol 12:611739. https://doi.org/10.3389/fmicb.2021.611739
Ghazouani A, Jebli MB, Shahzad U (2021) Impacts of environmental taxes and technologies on greenhouse gas emissions: contextual evidence from leading emitter European countries. Environ Sci Pollut Res 28:22758–22767. https://doi.org/10.1007/s11356-020-11911-9
Glasson CRK, Kinley RD, De Nys R, King N, Adams SL, Packer MA, Svenson J, Eason CT, Magnusson M (2022) Benefits and risks of including the bromoform containing seaweed Asparagopsis in feed for the reduction of methane production from ruminants. Algal Res 64:102673. https://doi.org/10.1016/j.algal.2022.102673
Global Carbon Project (2020) Global Methane Budget. https://earthobservatory.nasa.gov/images/146978/methane-emissions-continue-to-rise
Global Carbon Project (2021) Supplemental data of Global Carbon Budget 2021 (Version 1.0). https://doi.org/10.18160/gcp-2021
Global Climate Agreements: Global Climate Agreements: Successes and Failures, 2021. https://www.cfr.org/backgrounder/paris-global-climate-change-agreements
Global Warming Potential (2022) Climate Change: Atmospheric Carbon Dioxide. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
Holmes DE, Ueki T, Tang HY, Zhou J, Smith JA, Chaput G, Lovley DR (2019) A membrane-bound cytochrome enables *Methanosarcina acetivorans* to conserve energy from extracellular electron transfer. mBio 10(4):e00789–19. https://doi.org/10.1128/mBio.00789-19
Holmes DE, Smith JA (2016) Biologically produced methane as a renewable energy source. Adv Appl Microbiol 97:1–61. https://doi.org/10.1016/bs.aambs.2016.09.001
Ianc N, Boantă C, Gherghe I, Tomescu C (2020) Environmental impact of methane released from coal mines. MATEC Web of Conferences 305:00030. https://doi.org/10.1051/matecconf/202030500030
International Energy Agency: Greenhouse Gas Emissions from Energy: Overview, Paris, 2021. https://www.iea.org/reports/greenhouse-gas-emissions-from-energy-overview
International Energy Agency: Ministerial Meeting, 2022. https://www.iea.org/reports/india-energy-outlook-2021
International Energy Outlook, Global Methane Tracker, 2022. https://www.iea.org/reports/global-methane-tracker-2022/estimating-methane-emissions
International Energy Outlook, Greenhouse Gas Emissions from Energy, 2022. https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy
Ito K (2015) Suppression of methane gas emission from paddy fields, Nippon Steel And Sumitomo metal Technical Repor. No. 109. UDC 669.184.28: 553.981.4:631.4
Jackson RB, Saunois M, Bousquet P, Canadell JG, Poulter B, Stavert AR, Bergamaschi P, Niwa Y, Segers A, Tsuruta A (2020) Increasing anthropogenic CH_4 emissions arise equally from agricultural and fossil fuel sources. Environ Res Lett 15:071002. https://doi.org/10.1088/1748-9326/ab9ed2
Jarveoja J, Peichl M, Maddison M, Soosaar K, Vellak K, Karofeld E, Teemusk A, Mander U (2016) Impact of water table level on annual carbon and greenhouse gas balances of a restored peat extraction area. Biogeosciences 13(9):2637–2651. https://doi.org/10.5194/bg-13-2637-2016
Jeffrey LC, Maher DT, Chiri E, Leung PM, Nauer PA, Arndt SK, Tait DR, Greening C, Johnston SG (2021) Bark-dwelling methanotrophic bacteria decrease methane emissions from trees. Nat Commun 12:2127. https://doi.org/10.1038/s41467-021-22333-7
Joabsson A, Christensen TR, Wallén B (1999) Vascular plant controls on methane emissions from northern peatforming wetlands. Trends Ecol Evol 14(10):385–388. https://doi.org/10.1016/S0169-5347(99)01649-3
Jones MP, Krexner T, Bismarck A (2022) Repurposing Fischer-Tropsch and natural gas as bridging technologies for the energy revolution. Energy Convers Manag 267:115882. https://doi.org/10.1016/j.enconman.2022.115882
Jorgenson A, Birkholz R (2010) Assessing the causes of anthropogenic methane emissions in comparative perspective 1990–2005. Ecol Econ 69(12):2634–2643. https://doi.org/10.1016/j.ecolecon.2010.08.008
Juottonen H, Galand PE, Tuittila ES, Laine J, Fritze H, Yrjälä K (2005) Methanogen communities and Bacteria along an ecohydrological gradient in a northern raised bog complex. Environ Microbiol 7(10):1547–1557. https://doi.org/10.1111/j.1462-2920.2005.00838.x
Juottonen H, Galand PE, Yrjala K (2006) Detection of methanogenic Archaea in peat: comparison of PCR primers targeting the *mcrA* gene. Res Microbiol 157(10):914–921. https://doi.org/10.1016/j.resmic.2006.08.006
Kandel TP, Laerkea PE, Hoffmann CC, Elsgaard L (2019) Complete annual CO_2, CH_4, and N_2O balance of a temperate riparian wetland 12 years after rewetting. Ecol Eng 127:527–535. https://doi.org/10.1016/j.ecoleng.2017.12.019
Kemp CE, Ravikumar AP (2021) New technologies can cost effectively reduce oil and gas methane emissions, but policies will require careful design to establish mitigation equivalence. Environ Sci Technol 55:9140–9149. https://doi.org/10.1021/acs.est.1c03071
Kholod N, Evans M, Pilcher RC, Roshchanka V, Ruiz F, Cote M, Collings R (2020) Global methane emissions from coal mining to continue growing even with declining coal production. J Clean Prod 256:120489. https://doi.org/10.1016/j.jclepro.2020.120489
Korrensalo A, Mammarella I, Alekseychik P, Vesala T, Tuittila ES (2022) Plant mediated methane efflux from a boreal peatland complex. Plant Soil 471:375–392. https://doi.org/10.1007/s11104-021-05180-9
Krause L, McCullough KJ, Kane ES, Kolka RK, Chimner RA, Lilleskov EA (2021) Impacts of historical ditching on peat volume and carbon in northern Minnesota USA peatlands. J Environ Manage 296:113090. https://doi.org/10.1016/j.jenvman.2021.113090
Kühmaier M, Kral I, Kanzian C (2022) Greenhouse gas emissions of the forest supply chain in Austria in the year 2018. Sustainability 14:792. https://doi.org/10.3390/su14020792
Kulkarni MB, Ghanegaonkar PM (2019) Methane enrichment of biogas produced from floral waste: A potential energy source for rural India. Energy Sources Part a: Recover, Utilization, Environ Eff 41(22):2757–2768. https://doi.org/10.1080/15567036.2019.1571126
Kulkarni BN, Kulkarni NB, Anantharama V (2022) An empirical analysis of surface-level methane emission from anthropogenic sources in India. J Clean Prod 346:131101. https://doi.org/10.1016/j.jclepro.2022.131101
Laanbroek HJ (2010) Methane emission from natural wetlands: interplay between emergent macrophytes and soil microbial processes. A Mini-Review Ann Bot 105(1):141–153. https://doi.org/10.1093/aob/mcp201

Lan W, Yang C (2019) Ruminal methane production: associated microorganisms and the potential of applying hydrogen-utilizing bacteria for mitigation. Sci Total Environ 654:1270–1283. https://doi.org/10.1016/j.scitotenv.2018.11.180

Lebel ED, Lu HS, Vielstädte L, Kang M, Banner P, Fischer ML, Jackson RB (2020) Methane emissions from abandoned oil and gas wells in California. Environ Sci Technol 54:14617–14626. https://doi.org/10.1021/acs.est.0c05279

Lee SY, Holder GD (2001) Methane hydrates potential as a future energy source. Fuel Process Technol 71(1):181–186. https://doi.org/10.1016/S0378-3820(01)00145-X

Lenhart K, Weber B, Elbert W, Steinkamp J, Clough T, Crutzen P, Pöschl U, Keppler F (2015) Nitrous oxide and methane emissions from cryptogamic covers. Glob Chang Biol 21(10):3889–3900. https://doi.org/10.1111/gcb.12995

Li T, Zhang Q, Zhang W, Wang G, Lu Y, Yu L, Zhang R (2016) Prediction CH_4 emissions from the wetlands in the Sanjiang Plain of Northeastern China in the 21st century. PLoS ONE 11(7):e0158872. https://doi.org/10.1371/journal.pone.0158872

Li L, Wei S, Shen W (2020) The role of methane in plant physiology: a review. Plant Cell Rep 39:171–179. https://doi.org/10.1007/s00299-019-02478-y

Li M, Lv H, Lu Y, Wang D, Shi S, Li R (2022) Instantaneous discharge characteristics and its methane ignition mechanism of coal mine rock damage. Environ Sci Pollut Res 29:62495–62506. https://doi.org/10.1007/s11356-022-20104-5

Liang X, Kurniawa TA, Goh HH, Zhang D, Dai W, Liu H, Goh KC, Dzarfan-Othman MH (2022) Conversion of landfilled waste-to-electricity (WTE) for energy efficiency improvement in Shenzhen (China): a strategy to contribute to resource recovery of unused methane for generating renewable energy on-site. J Clean Prod 369:133078. https://doi.org/10.1016/j.jclepro.2022.133078

Liu Y, Cruz-Morales P, Zargar A, Belcher MS, Pang B, Englund E, Dan Q, Yin K, Keasling JD (2021) Biofuels for a sustainable future. Cell 184:1636–1647. https://doi.org/10.1016/j.cell.2021.01.052

Lupascu M, Akhtar H, Smith TEL, Sukri RS (2020) Post-fire carbon dynamics in the tropical peat swamp forests of Brunei reveal long-term elevated CH_4 flux. Glob Chang Biol 26(9):5125–5145. https://doi.org/10.1111/gcb.15195

Luta W, Ahmed OH, Omar L, Heng RKJ, Choo LNLK, Jalloh MB, Musah AA, Abdu A (2021) Water table fluctuation and methane emission in Pineapples (*Ananas comosus* (L.) Merr.) Cultivated on a Tropical Peatland. Agronomy 11:1448. https://doi.org/10.3390/agronomy11081448

Lynch J, Cain M, Frame D, Pierrehumbert R (2021) Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO_2-emitting sectors. Front Sustain Food Syst 4:518039. https://doi.org/10.3389/fsufs.2020.518039

Lyu Z, Whitman WB (2019) Transplanting the pathway engineering toolbox to methanogens. Curr Opin Biotechnol 59:46–54. https://doi.org/10.1016/j.copbio.2019.02.009

Maeck A, Delsontro T, McGinnis DF, Fischer H, Flury S, Schmidt M, Fietzek P, Lorke A (2013) Sediment trapping by dams creates methane emission hot spots. Environ Sci Technol 47(15):8130–8137. https://doi.org/10.1021/es4003907

Mand TD, Metcalf WW (2019) Energy conservation and hydrogenase function in methanogenic archaea, in particular the genus Methanosarcina. Microbiol Mol Biol Rev 83(4):e00020-e119. https://doi.org/10.1128/MMBR.00020-19

Manheim DC, Yeşiller N, Hanson JL (2021) Gas emissions from municipal solid waste landfills: a comprehensive review and analysis of global data. J Indian Inst Sci 101:625–657. https://doi.org/10.1007/s41745-021-00234-4

Martin G, Rissanen AJ, Garcia SL, Mehrshad M, Buck M, Peura S (2021) *Candidatus Methylumidiphilus* drives peaks in methanotrophic relative abundance in stratified lakes and ponds across northern landscapes. Front Microbiol 12:669937. https://doi.org/10.3389/fmicb.2021.669937

Massar M, Reza I, Rahman SM, Abdullah SMH, Jamal A, Al-Ismail FS (2021) Impacts of autonomous vehicles on greenhouse gas emissions-positive or negative? Int J Environ Res Public Health 18(11):5567. https://doi.org/10.3390/ijerph18115567

Mboowa D, Quereshi A, Bhattacharjee C, Tonny K, Dutta S (2017) Qualitative determination of energy potential and methane generation from municipal solid waste (MSW) in Dhanbad (India). Energy 123:386e391. https://doi.org/10.1016/j.energy.2017.02.009

McCalmont J, Kho LK, Teh YA, Lewis K, Chocholek M, Rumpang E, Hill T (2021) Short- and long-term carbon emissions from oil palm plantations converted from logged tropical peat swamp forest. Glob Chang Biol 11:2361–2376. https://doi.org/10.1111/gcb.15544

Meinshausen M, Lewis J, McGlade C, Gütschow J, Nicholls Z, Burdon R, Cozzi L, Hackmann B (2022) Realization of Paris Agreement pledges may limit warming just below 2 °C. Nature 604:304–309. https://doi.org/10.1038/s41586-022-04553-z

Menon S, Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox P, Dickinson R, Hauglustaine D, Heinze C, Holland E, Jacob D, Lohmann U, Ramachandran S, Dias P, Wofsy S, Zhang X (2007) Couplings between changes in the climate system and biogeochemistry. Climate Change 2007: The Physical Science Basis, S. Solomon et al., Eds., Cambridge University Press 499–587.

Methane possible (2023). Nat Clim Chang 13:1. https://doi.org/10.1038/s41558-022-01590-4

Miettinen J, Hooijer A, Vernimmen R, Liew SC, Susan E (2017) From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990. Environ Res Lett 12:024014. https://doi.org/10.1088/1748-9326/aa5b6f

Miller JF, Shah NN, Nelson CM, Ludlow JM, Clark DS (1988) Pressure and temperature effects on growth and methane production of the extreme thermophile *Methanococcus jannaschii*. Appl Environ Microbiol 54(12):3039–3042. https://doi.org/10.1128/aem.54.12.3039-3042.1988

Min R, Solaiman S, Waldrip HM, Parker D, Todd RW, Brauer D (2020) Dietary mitigation of enteric methane emissions from ruminants: a review of plant tannins mitigation options. Animal Nutrition 6(3):231–346. https://doi.org/10.1016/j.aninu.2020.05.002

Misiukiewicz A, Gao M, Filipiak W, Cieslak A, Patra AK, Szumacher-Strabel M (2021) Review: Methanogens and methane production in the digestive systems of nonruminant farm animals. Animal 15(1):100060. https://doi.org/10.1016/j.animal.2020.100060

Mitchell AL, Tkacik DS, Roscioli JR, Herndon SC, Yacovitch TI, Martinez DM, Vaughn TL, Williams LL, Sullivan MR, Floerchinger C, Omara M, Subramanian R, Zimmerle D, Marchese AJ, Robinson AL (2015) Measurements of methane emissions from natural gas gathering facilities and processing plants: measurement results. Environ Sci Technol 49:3219–3227. https://doi.org/10.1021/es5052809

Mizrahi I, Jami E (2018) Review: The compositional variation of the rumen microbiome and its effect on host performance and methane emission. Animal 12(s2):s220–s232. https://doi.org/10.1017/S1751731118001957

Mujiyo M, Sunarminto BH, Hanudin E, Widada J, Syamsiyah J (2017) Methane production potential of soil profile in organic paddy field. Soil Water Res 12(4):212–219. https://doi.org/10.17221/58/2016-SWR

Mwagona PC, Yao Y, Yuanqi S, Yu H (2021) Effect of water level fluctuation and nitrate concentration on soil-surface CO_2 and CH_4 emissions from Riparian freshwater marsh wetland. Wetlands 41:109. https://doi.org/10.1007/s13157-021-01501-x

Neale RE, Barnes PW, Robson TM et al (2021) Environmental effects of stratospheric ozone depletion, UV radiation, and interactions with climate change: UNEP Environmental Effects Assessment Panel, Update 2020. Photochem Photobiol Sci 20(1):1–67. https://doi.org/10.1007/s43630-020-00001-x

Nguyen AD, Lee EY (2021) Engineered methanotrophy: a sustainable solution for methane-based industrial biomanufacturing. Trends Biotechnol 39(4):381–396. https://doi.org/10.1016/j.tibtech.2020.07.007

Nie T, Zhang Z, Qi Z, Chen P, Sun Z, Liu X (2019) Characterizing spatiotemporal dynamics of CH_4 fluxes from Rice paddies of cold region in Heilongjiang Province under climate change. Int J Environ Res Public Health 16(5):692. https://doi.org/10.3390/ijerph16050692

Nisbet EG, Manning MR, Dlugokencky EJ et al (2019) Very strong atmospheric methane growth in the 4 years 2014–2017: implications for the Paris Agreement. Global Biogeochem Cycles 33(3):318–342. https://doi.org/10.1029/2018GB006009

Nisbet EG, Fisher RE, Lowry D, France JL, Allen G, Bakkaloglu S, Broderick TJ, Cain M, Coleman M, Fernandez J, Forster G, Griffiths PT, Iverach CP, Kelly BFJ, Manning MR, Nisbet-Jones PRB, Pyle JA, Townsend-Small A, Al-Shalaan A, Warwick N, Zazzeri G (2020) Methane mitigation: methods to reduce emissions, on the path to the Paris agreement. Rev Geophys 58(1):e2019RG000675. https://doi.org/10.1029/2019RG000675

Olsson L, Ye S, Yu X, Wei M, Krauss KW, Brix H (2015) Factors influencing CO_2 and CH_4 emissions from coastal wetlands in the Liaohe Delta, Northeast China. Biogeosciences 12(16):4965–4977. https://doi.org/10.5194/bg-12-4965-2015

Park JH, Kang HJ, Park KH, Park HD (2018) Direct interspecies electron transfer via conductive materials: a perspective for anaerobic digestion applications. Bioresour Technol 254:300–311. https://doi.org/10.1016/j.biortech.2018.01.095

Pieja AJ, Morse MC, Cal AJ (2017) Methane to bioproducts: the future of the bioeconomy? Curr Opin Chem Biol 41:123–131. https://doi.org/10.1016/j.cbpa.2017.10.024

Pieprzyk B, Hilje PR (2018) Influence of methane emissions on the GHG emissions of fossil fuels. Biofpr 13(3):535–551. https://doi.org/10.1002/bbb.1959

Pitz S, Megonigal JP (2017) Temperate Forest methane sink diminished by tree missions. New Phytol 214(4):1432–1439. https://doi.org/10.1111/nph.14559

Poppe K, Van Duinen L, Koeijer TD (2021) Reduction of greenhouse gases from Peat soils in Dutch agriculture. EuroChoices 20(2):38–45. https://doi.org/10.1111/1746-692X.12326

Prananto JA, Minasny B, Comeau LP, Rudiyanto R, Grace P (2020) Drainage increases CO_2 and N_2O emissions from tropical peat Soils. Glob Change Biol 26(8):4583–4600. https://doi.org/10.1111/gcb.15147

Prathaban M, Mythili R, Sharmila Devi N, Chandrasekar V (2017) Biological aspects of anaerobic digestion and its kinetics: an overview. J Microbiol Biotechnol Food Sci 6(4):1090–1097. https://doi.org/10.15414/jmbfs.2017.6.4.1090-1097

Prathiviraj R, Chellapandi P (2020a) Comparative genomic analysis reveals starvation survival systems in *Methanothermobacter thermoautotrophicus* ΔH. Anaerobe 64:102216. https://doi.org/10.1016/j.anaerobe.2020.102216

Prathiviraj R, Chellapandi P (2020b) Modeling a global regulatory network of *Methanothermobacter thermautotrophicus* strain ΔH. Network Model Health Inform Bioinform 9:17. https://doi.org/10.1007/s13721-020-0223-3

Prathiviraj R, Berchmans S, Chellapandi P (2019) Analysis of modularity in proteome-wide protein interaction networks of *Methanothermobacter thermautotrophicus* strain ΔH across metal-loving bacteria. J Proteins Proteomics 10:179–190. https://doi.org/10.1007/s42485-019-00019-5

Prathiviraj R, Chellapandi P (2019) Functional annotation of operome from *Methanothermobacter thermautotrophicus* ΔH: an insight to metabolic gap filling. Int J Biol Macromol 123:350–362. https://doi.org/10.1016/j.ijbiomac.2018.11.100

Pugh CA, Reed DE, Desai AR, Sulman BN (2018) Wetland flux controls: how does interacting water table levels and temperature influence carbon dioxide and methane fluxes in northern Wisconsin? Biogeochemistry 137:15–25. https://doi.org/10.1007/s10533-017-0414-x

Rahman MM, Aravindakshan S, Hoque MA, Rahman MA, Gulandaz, Jubaidur Rahman MA, Islam MT (2021) Conservation tillage (CT) for climate-smart sustainable intensification: Assessing the impact of CT on soil organic carbon accumulation, greenhouse gas emission and water footprint of wheat cultivation in Bangladesh. Environ Sustain Indic 10:100106. https://doi.org/10.1016/j.indic.2021.100106

Rahman MM, Yamamoto A (2020) Methane cycling in paddy field: a global warming issue. In (Ed.), Chapter-6, Agrometeorology. Intech Open. https://doi.org/10.5772/intechopen.94200

Ribeiro K, Pacheco FS, Ferreira JW, Sousa-Neto ER, Hastie A, Krieger Filho GC, Ometto JP (2020) Tropical peatlands and their contribution to the global carbon cycle and climate change. Glob Change Biol 27(3):489–505. https://doi.org/10.1111/gcb.15408

Richard D, Huang YC, Morales-Guio CG (2021) Recent advances in the electrochemical production of chemicals from methane. Curr Opin Electrochem 30:100793. https://doi.org/10.1016/j.coelec.2021.100793

Ritchie H, Roser M, Rosado P (2020) CO_2 and greenhouse gas emissions. (Online Resource) https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Ritchie H, Roser M, Rosado P (2020) CO_2 and greenhouse gas emissions. Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Rohlin L, Gunsalus RP (2010) Carbon-dependent control of electron transfer and central carbon pathway genes for methane biosynthesis in the Archaean, *Methanosarcina acetivorans* strain C2A. BMC Microbiol 10:62. http://www.biomedcentral.com/1471-2180/10/62

Rooney-Varga JN, Sterman JD, Fracassi E, Franck T, Kapmeier F, Kurker V, Johnston E, Jones AP, Rath K (2018) Combining role-play with interactive simulation to motivate informed climate action: evidence from the World Climate simulation. PLoS ONE 13(8):e0202877. https://doi.org/10.1371/journal.pone.0202877

Rosentreter JA, Borges AV, Deemer BR, Holgerson MA, Liu S, Song C, Melack J, Raymond PA, Duarte CM, Allen GH, Olefeldt D, Poulter B, Battin TI, Eyre BD (2021) Half of global methane emissions come from highly variable aquatic ecosystem sources. Nat Geosci 14:225–230. https://doi.org/10.1038/s41561-021-00715-2

Rothschild L, Mancinelli R (2001) Life in extreme environments. Nature 409:1092–1101. https://doi.org/10.1038/35059215

Rousk J, Bengtson P (2014) Microbial regulation of global biogeochemical cycles. Front Microbiol 5:103. https://doi.org/10.3389/fmicb.2014.00103

Saunois M, Jackson RB, Bousquet P, Poulter B, Canadell JG (2016) The growing role of methane in anthropogenic climate change. Environ Res Lett 11:120207. https://doi.org/10.1088/1748-9326/11/12/120207

Seemann M, Thunman H (2019) Methane synthesis: substitute natural gas from waste. Academic Press, Chapter-9, 2019:221–243. ISBN: 9780128155547. https://doi.org/10.1016/B978-0-12-815554-7.00009-X

Seo J, Jang I, Gebauer G, Kang H (2014) Abundance of methanogens, methanotrophic bacteria, and denitrifiers in rice paddy soils. Wetlands 34:213–223. https://doi.org/10.1007/s13157-013-0477-y

Sharma K, Sinha AK (2013) Global warming, human factors and environment: anthropological perspectives. Excel India Publishers. ISBN: 978–93–81361–89–4

Sindhu R, Binod P, Pandey A, Ankaram S, Duan Y, Awasthi MK (2019) Biofuel production from biomass: toward sustainable development. Current Developments in Biotechnology and Bioengineering, Chapter-5, Elsevier, 79–92, ISBN:9780444640833, https://doi.org/10.1016/B978-0-444-64083-3.00005-1

Singh CK, Kumar A, Roy SS (2018) Quantitative analysis of the methane gas emissions from municipal solid waste in India. Sci Rep 8:2913. https://doi.org/10.1038/s41598-018-21326-9

Singh PK, Kumar A, Banerjee K (2018) Methane emission and its variability in different land-uses of semi-arid region, Rajasthan. J Clim Change 4(2):67–75. https://doi.org/10.3233/JCC-1800014

Song C, Gardner KH, Klein SJW, Souza SP, Mo W (2018) Cradle-to-grave greenhouse gas emissions from dams in the United States of America. Renew Sust Energ 90:945–956. https://doi.org/10.1016/j.rser.2018.04.014

Specht E, Redemann T, Lorenz N (2016) Simplified mathematical model for calculating global warming through anthropogenic CO_2. Int J Therm Sci 102:1–8. https://doi.org/10.1016/j.ijthermalsci.2015.10.039

Staniaszek Z, Griffiths PT, Folberth GA, O'Connor FM, Abraham NL, Archibald AT (2022) The role of future anthropogenic methane emissions in air quality and climate. Clim Atmos Sci 5:21. https://doi.org/10.1038/s41612-022-00247-5

Steinlechner C, Junge H (2018) Renewable methane generation from carbon dioxide and sunlight. Angew Chem Int Ed Engl 57(1):44–45. https://doi.org/10.1002/anie.201709032

Stewart GJ, Nelson BS, Acton WJF, Vaughan AR, Hopkins JR, Yunus SSM, Hewitt CN, Wild O, Nemitz E, Gadi R, Sahu LK, Mandal TK, Gurjar BR, Rickard AR, Lee JD, Hamilton JF (2021) Emission estimates and inventories of non-methane volatile organic compounds from anthropogenic burning sources in India. Atmos Environ: X 11:100115. https://doi.org/10.1016/j.aeaoa.2021.100115

Sun K, Liu H, Fan H, Liu T, Zheng C (2021) Research progress on the application of feed additives in ruminal methane emission reduction: a review. PeerJ 9:e11151. https://doi.org/10.7717/peerj.11151

Taillardat P, Thompson BS, Garneau M, Trottier K, Friess DA (2020) Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus 10:20190129. https://doi.org/10.1098/rsfs.2019.0129

Timmers PH, Welte CU, Koehorst JJ, Plugge CM, Jetten MS, Stams AJ (2017) Reverse methanogenesis and respiration in methanotrophic archaea. Archaea 2017:1654237. https://doi.org/10.1155/2017/1654237

Torres-Sebastián MJ, Colli-Mull JG, Escobedo-Sánchez L, Martínez-Fong D, Rios-Solis L, Gutiérrez-Castillo ME, López-Jiménez G, Moreno-Rivera ML, Tovar-Gálvez LR, Espadas-Álvarez AJ (2021) Methane, a renewable biofuel: from organic waste to bioenergy. Biofuels 13:907–917.https://doi.org/10.1080/17597269.2021.2016105

Tseten T, Sanjorjo RA, Kwon M, Kim SW (2022) Strategies to mitigate enteric methane emissions from ruminant animals. J Microbiol Biotechnol 32(3):269–277. https://doi.org/10.4014/jmb.2202.02019

Turner AJ, Frankenberg C, Kort EA (2019) Interpreting contemporary trends in atmospheric methane. Proc Natl Acad Sci USA 116(8):2805–2813. https://doi.org/10.1073/pnas.1814297116

UN News report, Global perspective Human stories, UN climate report: It's 'now or never' to limit global warming to 1.5 degrees, 2022. https://news.un.org/en/story/2022/04/1115452

Van der Nat FJ, Middelburg JJ (2000) Methane emission from tidal freshwater marshes. Biogeochemistry 49(2):103–121. https://doi.org/10.1023/A:1006333225100

Varis O, Kummu M, Härkönen S, Huttunen JT (2012) Greenhouse gas emissions from reservoirs. In: Tortajada C, Altinbilek D, Biswas A (eds) Impacts of large dams: a global assessment. Water Resources Development and Management. Springer, Berlin, Heidelberg. Page: 69–94. https://doi.org/10.1007/978-3-642-23571-9_4

Wang W, Lee DJ (2021) Direct interspecies electron transfer mechanism in enhanced methanogenesis: a mini-review. Bioresour Technol 330:124980. https://doi.org/10.1016/j.biortech.2021.124980

Wang ZP, Han SJ, Li HL, Deng FD, Zheng YH, Liu HF, Han XG (2017) Methane production explained largely by water content in the heartwood of living trees in upland forests. J Geophys Res Biogeosci 122(10):2479–2489. https://doi.org/10.1002/2017JG003991

Wang Y, Levis JW, Barlaz MA (2021a) Life-cycle assessment of a regulatory compliant US Municipal solid waste landfill. Environ Sci Technol 55:13583–13592. https://doi.org/10.1021/acs.est.1c02526

Wang Z, Liu S, Qin Y (2021b) Coal wettability in coalbed methane production: a critical review. Fuel 303:121277. https://doi.org/10.1016/j.fuel.2021.121277

Wang Y, Tang J, Li F, Xie D, Zuo F, Yu X, Xu Y, Chen J (2022) Measurement of methane emissions from CNG fueling stations in East China. Environ Sci Pollut Res 29:71949–71957. https://doi.org/10.1007/s11356-022-20929-0

Warmuzinski K (2008) Harnessing methane emissions from coal mining. Process Saf Environ Prot 8(6):315–320. https://doi.org/10.1016/j.psep.2008.04.003

Williams JP, Regehr A, Kang M (2021) Methane emissions from abandoned oil and gas wells in Canada and the United States. Environ Sci Technol 55:563–570. https://doi.org/10.1021/acs.est.0c04265

Wilson RM, Hopple AM, Tfaily MM, Sebestyen SD, Schadt CW, Pfeifer-Meister L, Medvedeff C, McFarlane KJ, Kostka JE, Kolton M, Kolka RK, Kluber LA, Keller JK, Guilderson TP, Griffiths NA, Chanton JP, Bridgham SD, Hanson PJ (2016) Stability of peatland carbon to rising temperatures. Nat Commun 7:13723. https://doi.org/10.1038/ncomms13723

Wolfe RS (1993) An historical overview of methanogenesis. In: Ferry, J.G. (eds) Methanogenesis. Chapman & Hall Microbiology Series. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-2391-8_1.ISBN:978-1-4615-2391-8

World Meteorological Organization, The World Data Centre for Greenhouse Gases (WDCGG), 2019. https://www.env.go.jp/en/headline/2397.html

World Meteorological Organization, Global Annual to Decadal Climate Update, (2022) https://library.wmo.int/doc_num.php?explnum_id=11175

Xie SP, Kosaka Y, Okumura Y (2016) Distinct energy budgets for anthropogenic and natural changes during global warming hiatus. Nature Geosci 9:29–33. https://doi.org/10.1038/ngeo2581

Xu T, Weng B, Yan D, Wang K, Li X, Bi W, Li M, Cheng X, Liu Y (2019) Wetlands of international importance: status, threats, and future protection. Int J Environ Res Public Health 16(10):1818. https://doi.org/10.3390/ijerph16101818

Xu R, Fang S, Zhang L, Huang W, Shao Q, Fang F, Luo J (2021) Distribution patterns of functional microbial community in anaerobic digesters under different operational circumstances: a review. Bioresour Technol 341:125823. https://doi.org/10.1016/j.biortech.2021.125823

Yang B, Zhongke Bai Z, Zhang J (2021) Environmental impact of mining-associated carbon emissions and analysis of cleaner production strategies in China. Environ Sci Pollut Res 28:13649–13659. https://doi.org/10.1007/s11356-020-11551-z

Zhang C, Song Z, Bai Q, Zhang L, Chen J (2022) Intensive field measurements for characterizing the permeability and methane release with the treatment process of pressure-relief mining. Sci Rep 12:14847. https://doi.org/10.1038/s41598-022-19283-5

Zhang Y, Song C, Wang X, Chen N, Zhang H, Du Y, Zhang Z, Zhua XH (2022) Warming effects on the flux of CH_4 from peatland mesocosms are regulated by plant species composition: Richness and functional types. Sci Total Environ 806(Pt4):150831. https://doi.org/10.1016/j.scitotenv.2021.150831

Zhang Z, Poulter B, Knox S, Stavert A, McNicol G, Fluet-Chouinard E, Feinberg A, Zhao Y, Bousquet P, Canadell JG, Ganesan A, Hugelius G, Hurtt G, Jackson RB, Patra PK, Saunois M, Höglund-Isaksson L, Huang C, Chatterjee A, Li X (2021) Anthropogenic emission is the main contributor to the rise of atmospheric methane during 1993–2017. Natl Sci Rev 9(5):nwab200. https://doi.org/10.1093/nsr/nwab200

Zhao Y, Zhao G (2021) Decreasing ruminal methane production through enhancing the sulfate reduction pathway. Anim Nutr 9:320–326. https://doi.org/10.1016/j.aninu.2022.01.006

Zheng K, Tan L, Sun Y, Wu Y, Duan Z, Xu Y, Gao C (2021) Impacts of climate change and anthropogenic activities on vegetation change: evidence from typical areas in China. Ecol Indic 126:107648. ISSN:1470–160X. https://doi.org/10.1016/j.ecolind.2021.107648

Zou Y, Duan X, Xue Z, E M, Sun M, Lu X, Jiang M, Yu X (2018) Water use conflict between wetland and agriculture. J Environ Manage 224:140-146. https://doi.org/10.1016/j.jenvman.2018.07.052