nature climate change

Analysis

https://doi.org/10.1038/s41558-024-01947-x

Global trend of methane abatement inventions and widening mismatch with methane emissions

In the format provided by the authors and unedited

This PDF file includes:

Supplementary Tables Table 1
Supplementary Notes SN1 to SN3
Supplementary Figures Fig.1 to Fig.6
Supplementary References

List of Supplementary Tables

List of Supplementary Notes

List of Supplementary Figures

Supplementary Table 1 Technological field, code, and keyword for identification and basic definition of MTATs.

Technology field	Technology subfield	CPC/IPC codes and keywords	Basic definition
Agriculture	Rice cultivation	Y02P60/22	Technologies aiming to reduce methane emissions from rice cultivation, such as advanced cultivation methods, seed breeding, and methane-inhibited irrigation technologies
	Land use management	Y02P60/30	Technologies aiming to reduce methane emissions or increase methane sinks from land use, such as soil improvement, cropland management, and carbon flux monitor technologies
	Afforestation and reforestation	Y02P60/40	Afforestation and reforestation technologies for fostering carbon sinks, such as vertical and space greening, interplanting technologies, and protection devices for afforestation seedlings
	Livestock management	Y02P60/50; Y02P60/52; Y02C20/20 while not belonging to IPC class A	Technologies aiming to reduce methane emissions from livestock and poultry farming, such as breeding, forage improvement, manipulation of rumen fermentation, biogas digester, and manure disposal technologies
Fossil energy	Coal mine	Y02C20/20 while not belonging to IPC class A and Y02E with the keyword set of {coal, coal mine, coal bed, coalbed, coal well, coal methane, coalbed gas, coal mining, coal extraction, coal dressing, CMM, mine gas}	Technologies aiming to reduce methane emissions from coal mines, such as coalbed automatic monitoring and recovery, low-concentration or ventilation gas use, and abandoned coal mine treatment technologies
	Fugitive emission controlling in oil and gas supply	Y02C20/20 while not belonging to IPC class A and Y02E with two keyword sets of {methane, fugitive emission, oil, natural gas, gas, mine} and {leak, leakage, LDAR, monitor, detect, sensor, sensing, satellite, aircraft, aerobat, infrared camera}	Leak detection and repair technologies aiming to reduce fugitive emissions in oil and natural gas supply, such as satellite monitor, infrared camera, pipeline maintenance, intelligent sensing, and on-site detect technologies

	Vented or flared emission controlling in oil and gas supply	Y02C20/20 while not belonging to IPC class A and Y02E with the two keyword sets of {methane, vented emission, flared emission, venting emission, flaring emission, oil, natural gas, gas, mine} and {pneumatic device, pneumatic controller, pneumatic pump, electrical pump, valve, compressor seal, rod, electric motor, instrument air system, vapour recovery unit, VRU, blowdown, flare, plunger, lift, liquid unload}	Technologies aiming to reduce vented or flared methane emissions in oil and natural gas supply, such as low or zero-bleed, plunger lift, vented gas recovery, vapour recovery unit, electric pump and motor, instrument air system, compressor seal, blowdown capture, portable flare, high-efficient liquid unloading, and abandoned well management technologies
	General fossil energy technologies	Y02C20/20 while not belonging to IPC class A and Y02E with the two keyword sets of {methane, coal, oil, natural gas, gas, mine} and {methane-reducing catalyst, methane-reduced catalyst, methane catalytic, methane catalysator, microturbine, pipeline pump-down, green completion}	Comprehensive technologies for reducing fugitive, vented or flared methane emissions from coal mines or in oil and gas supply, such as methane-reducing catalyst, pipeline pump-down, portable microturbine, green completion, and post-mining restoring and management technologies
Waste treatment	Wastewater treatment	Y02W10/10; Y02W10/20; Y02W10/30; Y02W10/33; Y02W10/37; Y02W10/40	Technologies aiming to reduce methane emissions from wastewater treatment, such as methane-reduced biological treatment, advanced sewage treatment devices, and resourcing technologies of wastewater, sewage or sludge
	Waste landfill	Y02W30/30	Technologies aiming to mitigate methane emissions from waste landfill, such as landfill gas collection and recovery, landfill covering layer and impervious technologies
	Waste incineration	Y02E50/30; Y02E20/12 without the keyword “biomass”	Waste-to-energy technologies for methane abatement, such as waste incineration power generation, waste-to-alcohol, and other technologies that convert wastes into energy or fuels
	Biomass waste treatment	Y02W30/40	Biomass or biomass-mixed waste treatment technologies for emissions abatement, such as bio-organic fraction processing, waste-to-fertilizer technologies, and other resourcing technologies of biomass or bio-mixture waste materials

	Packaging waste recycling	Y02W30/80; Y02W90/10	Packaging waste recycling technologies for emissions abatement, such as bio-package, degradable packing materials, and other recycling technologies for packing containers
	Organic waste recycling	Y02W30/62; Y02W30/64; Y02W30/66; Y02W30/74; Y02W30/78	Recycling technologies of organic waste materials, such as paper, rubber, plastics, fiber and textile and other organic wastes but excluding biomass and packaging wastes
Biomass	Biofuels	Y02E50/10	Biomass-to-fuel technologies, such as bioethanol, biodiesel, biomass densification, and other technologies to produce biofuels from biomass or biomass mixtures
	Biomass combustion	Y02E20/12 with the keyword "biomass"; Y02E20/30 with the keyword "biomass"	Technologies aiming to reduce methane emissions from incomplete biomass burning, such as biomass treatment, biomass boiler and stove technologies, and heat circulating and waste heat reuse technologies in biomass combustion
Cross-cutting enabling technologies	Atmospheric methane removal	Y02C20/20 excluding those belonging to IPC class A and those classified into fossil energy fields; Y02C with the two keyword sets of {methane} and {direct air capture, direct atmospheric capture, DAC, removal, conversion, destruct, oxidize, oxidizing, oxidation, negative emission, NET, zeolite, porous polymer network, PPN, adsorb, metal-organic framework, iron-salt aerosol, catalytic paint, catalyst paint}	Technologies aiming at direct atmospheric capture and removal of methane, such as zeolite, porous polymer network, methane adsorbent, methane-oxidative catalyst, metal-organic framework, iron-salt aerosol, methane photocatalyst, and other technologies to accelerate methane oxidation, destruction, and removal from the atmosphere
	Carbon pricing and management	Y02P90/80; Y02P90/82; Y02P90/84; Y02P90/845; Y02P90/90; Y02P90/95	Carbon pricing and management technologies for emissions abatement, such as energy audit, emissions inventory and reporting, carbon trading, methane tax, climate finance, and other carbon planning and management technologies

Supplementary Notes

Supplementary Note 1. Country classification

To capture the distribution pattern of MTAT inventions by development level in more detail, and to maintain the compatibility with existing country classifications defined by the United Nations Conference on Trade and Development (UNCTAD), the World Economic Situation and Prospects (WESP) and the Group of Twenty (G20)[1-3], we classify the countries and dependent territories into four groups, – developed countries, emerging economies, the least developed countries (LDCs), and other developing countries (the rest developing countries excluding emerging economies and LDCs). The detailed country classification used in this study is as follows:

The group of developed countries[1,2]: Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia Lithuania, Luxembourg, Malta, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, United States.

The group of emerging economies[3]: China, South Korea, Brazil, Russia, Saudi Arabia, India, Turkey, Mexico, South Africa, Argentina, and Indonesia.

The group of least developed countries[2]: Afghanistan, Angola, Bangladesh, Benin, Bhutan, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Kiribati, Lao People’s Democratic Republic, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Myanmar, Nepal, Niger, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Solomon Islands, Somalia, South Sudan, Sudan, Tanzania, Timor Leste, Togo, Tuvalu, Uganda, Yemen, Zambia.

The group of other developing countries: the remaining instances of developing countries after excluding emerging economies and LDCs.

In addition, it should be noticed that the classification of South Korea has been upgraded by the UNCTAD to be a developed country in July 2021[1]. However, under the WESP and the G20, this country is usually discussed as a major emerging economy. In this study, we also analyze South Korea as an emerging economy with the aim to better explore its catching-up progress of MTATs.

Supplementary Note 2. Analysis of robustness test

The major results and findings of this study are obtained based on using international patent families (IPFs) being applied, regardless of whether they are granted, to represent high-quality MTAT inventions. We adopt two alternative methods to test the robustness of the major results: one is using granted IPFs to represent high-quality inventions, and the other is adopting the top-10% highly cited patent families as a proxy for high-quality inventions. The results based on granted IPFs are presented in Supplementary Figs. 1–3, which are highly consistent with findings in the main text. Additionally, the results measured by citation-based high-quality MTAT inventions are shown in Supplementary Figs. 4–6, which indicate slight differences but are also essentially consistent with the findings in the main text. More specific analysis is as follows:

Regarding the global inventive trend, Supplementary Fig.1 shows that the granted inventions and granted high-quality inventions of MTATs began a significant declining trend since 2016 and 2010, respectively. The results are essentially consistent with the findings in the main text, and the beginning of the decline in granted MTAT inventions one year earlier is probably due to the time-lag from patent application to patent grant. Besides, Supplementary Fig.4 shows that citation-based high-quality MTAT inventions did not start a declining trend in 2010. This is mainly because China's astonishing surge in patent applications and thereby citations, particularly for singleton patents, has driven up the overall trend. However, excluding China, citation-based high-quality inventions exhibit a declining trend from 2010 to 2019, which is similar to that obtained based on the IPFs.

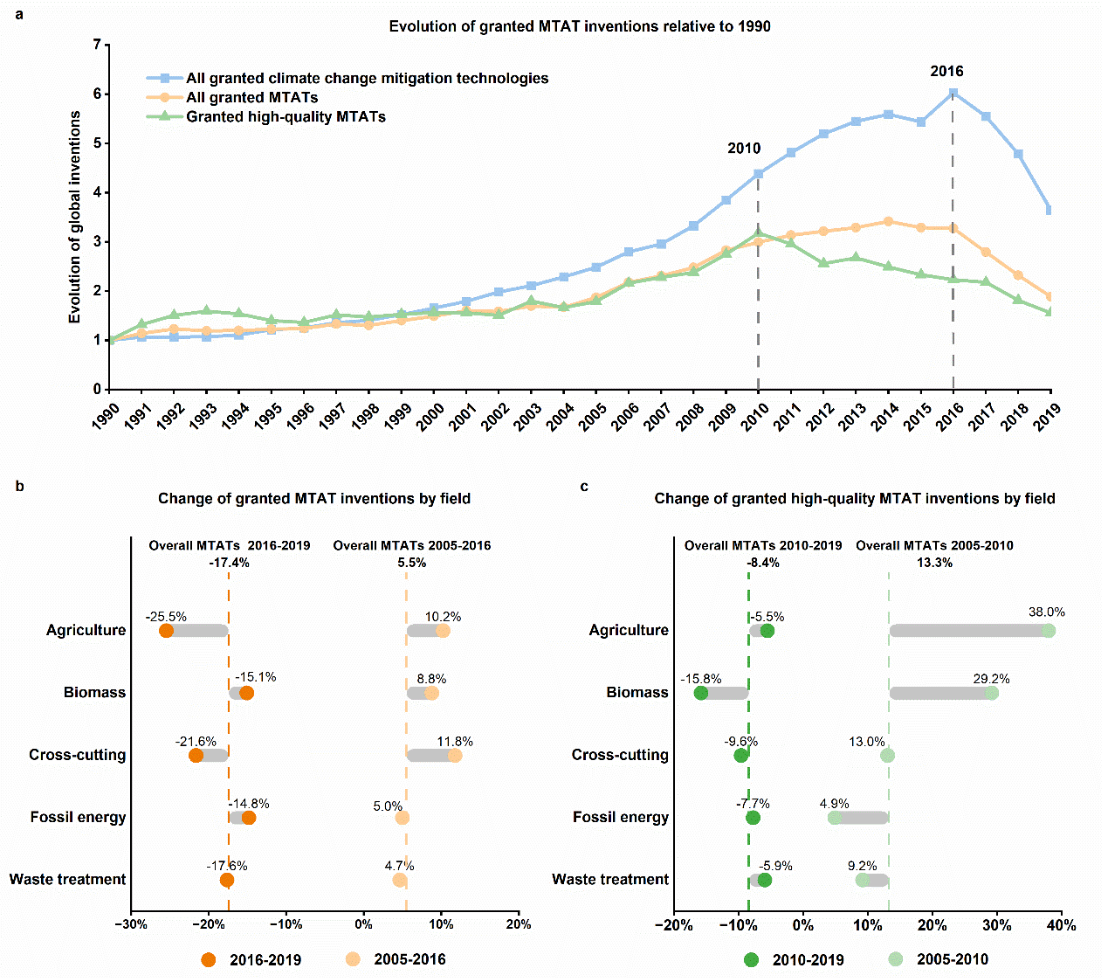
Regarding the sectoral-level distribution of inventions, Supplementary Fig.2 and Fig.5 present highly consistent findings with the main text, indicating a concentration of global MTAT inventions in the waste treatment and biomass sectors rather than the agricultural and fossil energy sectors.

As regard to the national-level distribution of inventions, Supplementary Fig.3 displays highly consistent results with that in the main text, while Supplementary Fig.6 shows generally consistent but slightly different results. Specifically, the concentration of high-quality MTAT inventions in a few developed countries and together with China and South Korea are generally robust between IPF-based and citation-based methods. The slight difference is that several emerging economies, namely China, South Korea, Russia, Saudi Arabia, and India, experience the faster growth and the better ranking in high-quality inventions measured by patent citations rather than IPFs, which indicates a catch-up process of MTATs in these countries. Overall, the major findings of this study are robust.

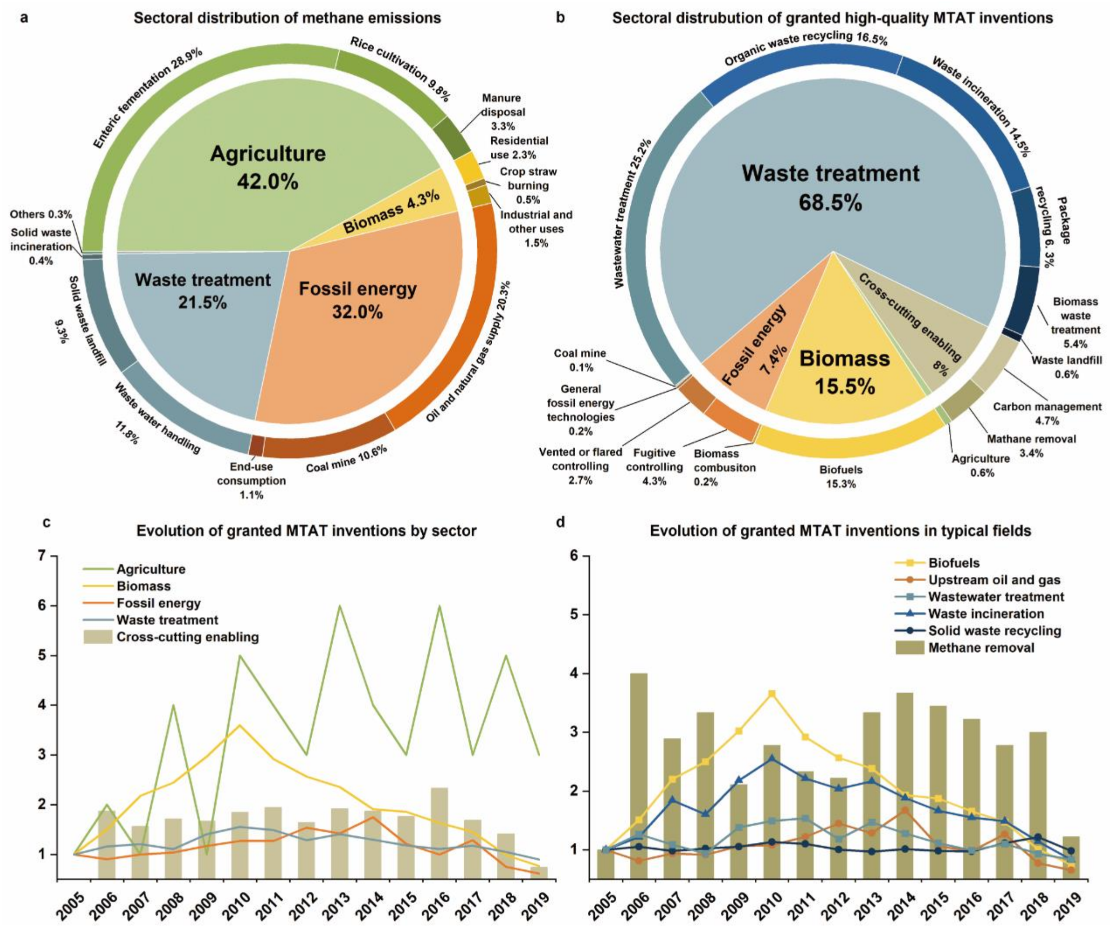
Supplementary Note 3. Uncertainty analysis

Uncertainties in this study mainly originate from the following two sources. One type of uncertainty arises from the uncertainties in patent data and our selection criteria. Due to the immature patent system and incomplete coverage of patent information in less developed regions, such as South and Southeast Asia, Africa, and Latin America, their data on MTAT patent families may be underestimated. Additionally, we use the keyword "methane" rather than "CH_4" during patent searching to avoid false positives caused by subscripts, which may lead to possible omissions of some patents. Against this, we utilize fossil energy MTATs as an experiment to compare the results solely searched with "methane" and those selected by using both "methane" and "CH_4". The results showed that only a few dozens, or less than one percent of the overall fossil energy MTAT patents were omitted. The other type of uncertainty stems from the uncertainties in methane emissions estimates. Methane emissions data used in this study are collected from the EDGAR, which calculates methane emissions relying mainly on bottom-up methods. According to the existing literature, methane emissions estimated by the EDGAR have uncertainty intervals of approximately (−60 %, +90%) for fossil energy, (−30 %, +40%) for agriculture, and (−80 %, +80%) for waste treatment (the 95 % confidence of a log-normal distribution)[4,5].

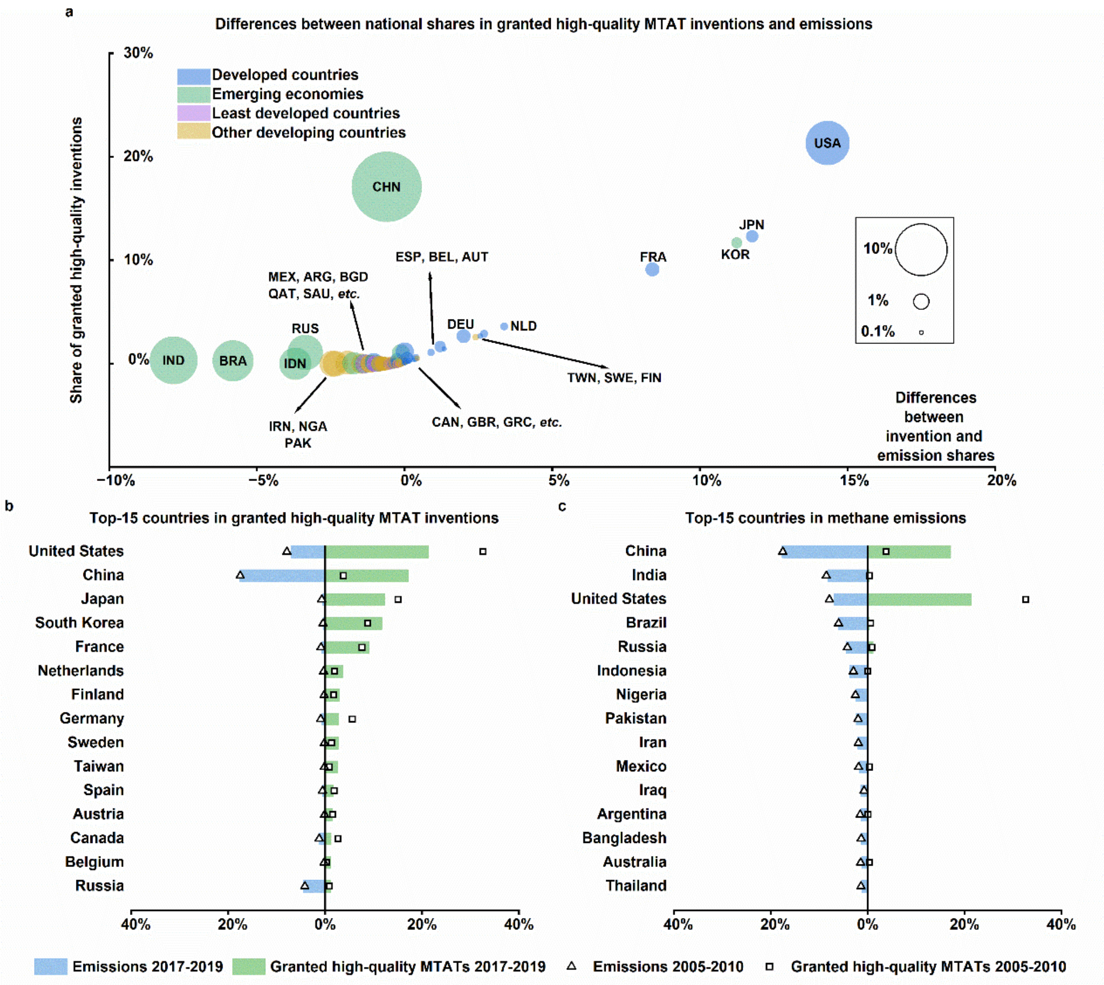
Supplementary Figures



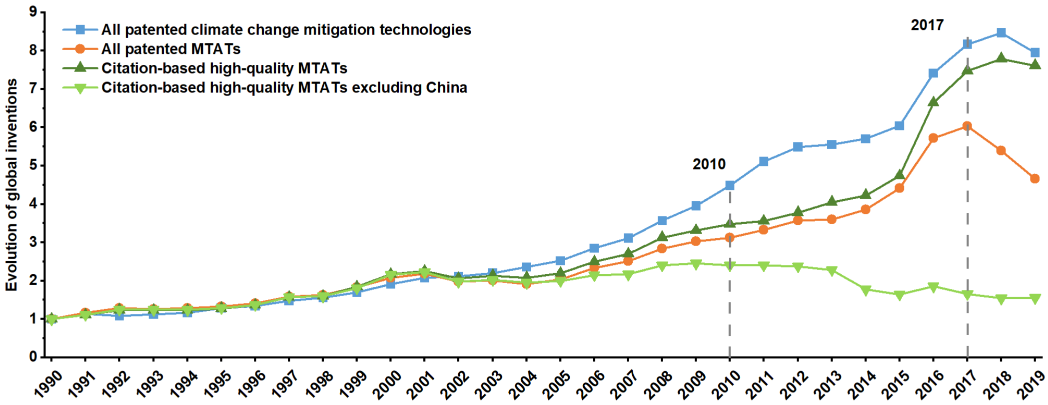
Supplementary Fig.1 Global trend of granted MTAT inventions. Based on a baseline index of 1 in 1990, **a** presents the global trend of granted and granted high-quality MTAT inventions from 1990 to 2019; **b** shows the annual average rate of change in granted MTAT inventions between the 2005–2016 and 2016–2019 periods, while **c** presents that in granted high-quality inventions between the 2005–2010 and 2010–2019 periods, in which the inflection points of 2016 and 2010 are identified based on graph analysis and gradient change-point detection. Cross-cutting represents cross-cutting enabling technologies.



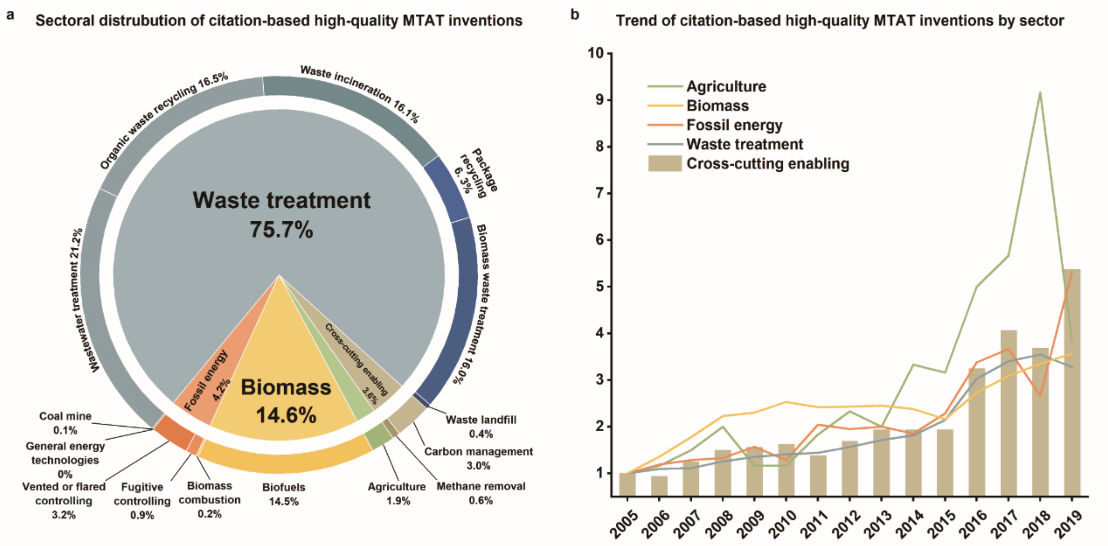
Supplementary Fig.2 Sectoral distribution and trend of granted high-quality MTAT inventions. **a** and **b** show the sectoral distribution of global methane emissions and granted high-quality MTAT inventions in 2017-2019, respectively; and based on a baseline index of 1 in 2005, **c** and **d** display the developing trend of granted high-quality MTAT inventions in five major sectors and six typical technology subfields from 2005 to 2019, respectively. In **d**, the subfield of upstream oil and gas includes fugitive, vented or flared methane controlling technologies for oil and natural gas supply, and that of solid waste recycling comprises biomass waste treatment and package and organic waste recycling technologies.



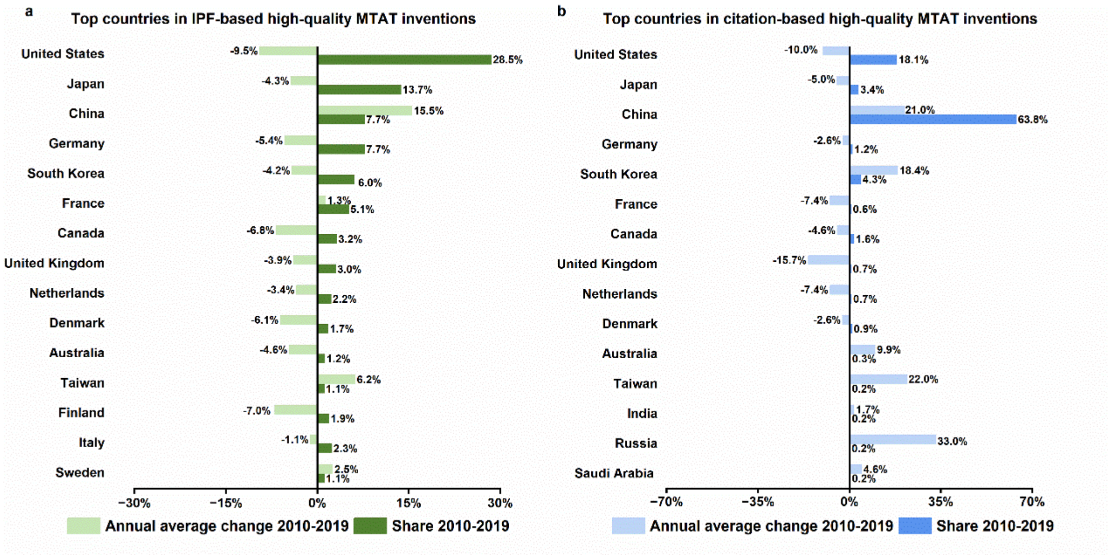
Supplementary Fig.3 National-level distribution of methane emissions and granted high-quality MTAT inventions. **a** shows the mismatched distribution of methane emissions and granted high-quality MTAT inventions across countries or regions during 2017–2019, where the circle areas represent the scale of national emissions, and the differences between invention and emission shares are calculated by subtracting the percentage of national emissions from that of granted high-quality inventions; **b** and **c** show the proportion of the top-15 inventing and emitting countries, respectively, in global granted high-quality MTAT inventions and emissions during the 2005–2010 and 2017–2019 periods. The period 2005–2010 is selected to represent an accelerated growth stage in MTAT inventions, while 2017–2019 representing a recent declining period. Taiwan refers to the Taiwan province of China.



Supplementary Fig.4 Global trend of citation-based high-quality MTAT inventions. Based on a baseline index of 1 in 1990, the figure presents the global trends of all patented and citation-based high-quality MTAT inventions from 1990 to 2019. Citation-based high-quality MTATs refer to the top-10% highly cited MTAT inventions after controlling the technological field and filing year.



Supplementary Fig.5 Sectoral distribution and trend of citation-based high-quality MTAT inventions. a presents the sectoral distribution of the top-10% highly cited high-quality inventions in 2017-2019; and based on a baseline index of 1 in 2005, **b** shows the developing trend of the top-10% highly cited MTAT inventions by sector from 2005 to 2019.



Supplementary Fig.6 Comparison of the top-15 countries in high-quality MTAT inventions measured by two methods. a presents the percentage of the top-15 countries in global IPF-based high-quality MTAT inventions and their annual average changes during 2010-2019, while **b** shows those measured by the top-10% highly cited high-quality inventions. The IPF is an abbreviation for international patent family, and Taiwan represents the Taiwan province of China.

Supplementary References

1. Trade and Development Board, Sixty-Eighth Session (United Nations Conference on Trade and Development (UNCTAD), 2023); https://unctad.org/meeting/trade-and-development-board-sixty-eighth-session
2. The Group of Twenty (G20) – Background Brief (The Group of Twenty, 2023); https://www.g20.org/en/about-g20/#members
3. World Economic Situation and Prospects (United Nations, 2023).
4. Saunois, M.et al. The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data*, **12**, 1561–1623 (2020).
5. Solazzo, E., Crippa, M., Guizzardi, D., Muntean, M., Choulga, M., and Janssens-Maenhout, G. Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases, *Atmos. Chem. Phys.* **21**, 5655–5683 (2021).