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

Received: 27 June 2023

Accepted: 2 February 2024

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Substantially reducing methane emissions is the fastest way to repress near-term warming and is an essential prerequisite for reaching the 1.5 °C target. However, knowledge about the global invention trend, sectoral and national distribution and international diffusion of methane-targeted abatement technologies (MTATs) remains limited. On the basis of patent data, we identify more than 175,000 MTAT inventions applied between 1990 and 2019 by 133 countries or dependent territories. Our results revealed that after sustained growth of more than fourfold, the number of global high-quality MTAT inventions declined by 3.5% annually from 2010 to 2019. The sectoral and national-level distributions of MTAT inventions and methane emissions are strongly mismatched. Additionally, the international diffusion of MTATs is 11.1% lower than that of overall climate change mitigation technologies and most transfers occur between developed countries or flow to China, South Korea and Brazil; however, other developing countries and the least developed countries are rarely involved.

The amount of atmospheric methane (CH_4) has surged rapidly since 2005 and hit a new record high in 2022 (ref. 1). The globally averaged atmospheric concentration of methane has more than doubled since preindustrial times and is responsible for approximately one-third of global warming[2–5]. Methane, although powerful, is a short-lived climate pollutant with an atmospheric lifetime of roughly one decade[6]. Such a short life cycle means that methane abatement can gain immediate payoffs from decreased atmospheric abundance and thereby weakened climate forcing. Substantially reducing anthropogenic methane emissions has thus been identified as the fastest way to curb near-term warming and the most effective strategy for pursuing the 1.5 °C target[7–9]. Moreover, anthropogenic methane emissions contribute to the formation of ground-level ozone, causing nearly half-a-million premature deaths each year and impairing agricultural productivity[10,11]. Hence, decreasing methane emissions will provide cobenefits for improving public health and alleviating food shortages.

Given the great leverage of methane in mitigating climate change and facilitating the achievement of several sustainable development goals, the COP26 launched the Global Methane Pledge initiative, which aimed to abate anthropogenic methane emissions by at least 30% by 2030 (ref. 12). A host of technologies and measures have been proposed in the recent literature, presenting a general blueprint for methane abatement[13–15]. The potentials and costs of methane-targeted abatement technologies (MTATs) have been broadly examined for major sectors or systemwide[13,15–18]. Despite the considerable estimated potentials[9,19–21], it has been acknowledged that technologies available at present fall short of the methane abatements required for the 1.5 °C target[7,13,22–24]. Hence, expediting innovation in MTATs is urgently needed to close such a gap. Recent studies based on patent data have shown global trends in climate change mitigation and adaptation technologies[25–27] and energy technologies[28–30]. However, knowledge about global inventions in MTATs remains limited.

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Table 1 | Technology field, brief definition and amount of MTAT inventions in 1990–2019

Technology field	Brief definition	Amount of all patented inventions	Amount of high-quality inventions
Agriculture	Technologies which aim to reduce methane emissions from rice cultivation, land use and livestock or to increase carbon sinks by afforestation and reforestation, such as breeding, methane-inhibited irrigation, rumen fermentation manipulation, manure management and interplanting technologies.	2,112	179
Fossil energy	Technologies which aim to reduce fugitive, vented or flared methane emissions from coal mines or oil and natural gas supply, such as methane extraction, low-concentration gas use, leak detect and repair, satellite monitor, blowdown capture, portable flare and green completion technologies.	7,614	2,339
Waste treatment	Technologies which aim to reduce methane emissions from wastewater and solid waste treatment, such as methane-reduced wastewater and sludge treatment, landfill gas collection, waste to energy or fertilizer technologies and organic waste separation and recycling technologies.	156,684	25,896
Biomass	Technologies which aim to reduce methane emissions from biomass, such as bioethanol, biodiesel, integrated biofuel utilization and other biomass-to-fuel technologies, as well as biomass densification, biomass boiler and stove and other high-efficient biomass combustion technologies.	27,365	8,087
Cross-cutting enabling	Methane reduction or removal technologies that can be deployed beyond specific sectors or facilitate the application of other technologies, such as carbon accounting, pricing and management, methane tax, direct air capture of methane and atmospheric methane destruction technologies.	6,886	2,653
Overall MTATs		175,963	32,616

High-quality inventions refer to inventions that are filed in at least two countries or regions to seek to be protected internationally. The sum of inventions in all technology fields does not equal the number of overall MTAT inventions because some inventions may pertain to several technology fields.

Moreover, there are large mismatches between growth sources and abatement potentials in terms of global methane emissions. Driven by expanding and increasingly affluent population, the agricultural sector is widely projected to be the dominant growth source of methane emissions[7,13,21]. However, the expected technological potential of methane abatement in this sector is very limited, urgently calling for new breakthroughs[22,31–33]. Additionally, most growths in future methane emissions are projected to come from countries currently less developed or poverty-stricken, such as the constantly increasing emissions caused by livestock farming, waste disposal or rice cropping from African, Latin American and Asian countries[13,17,21]. Unfortunately, both the technical capacity and reserve for methane control are inadequate in these regions[25]. Therefore, accelerating the international transfer and diffusion of related technologies is an indispensable and cost-effective strategy to facilitate methane abatement but this issue has rarely been studied.

To fill this gap, we make a comprehensive and up-to-date analysis of global trends in the invention and diffusion of MTATs. By combining methane abatement pathways with the Y02 scheme customized by the European Patent Office (EPO) for climate-friendly technologies[34], we develop a systematic five-step search method to identify MTAT invention patents. The search scope covers all inventions that specifically target reducing methane emissions or fostering methane removal. On the one hand, we focus uniquely on MTATs and rule out those targeting other types of GHGs but with CH_4 cobenefits, such as photovoltaic power technologies[28]. On the other hand, we cover technologies for both methane reduction and removal, for example zeolites and iron-salt aerosols[23,24]. The identified MTAT inventions are categorized into five fields (Table 1) and each field is further divided into several subfields to inform more granular analysis (Methods; Supplementary Table 1).

Additionally, although patents have been broadly used to measure innovation, they have defects of poor international comparability and wide-ranging quality[35–37]. Hence, we adopt patent families (PFs) instead of patent counts as a more reliable metric for MTAT innovation[38,39] and we focus on international patent families (IPFs) filed in at least two jurisdictions and apply them to represent high-quality inventions. Overall, we document 175,963 PFs on MTATs applied between 1990 and 2019 by 133 countries or dependent territories and 32,616 of them are high-quality IPFs.

Recent decline in global MTAT inventions

The volume of all patented inventions of MTATs increased more than sixfold from 1990 to 2017, with an average annual growth rate of 6.9% (Fig. 1a). The growth of all patented MTAT inventions began to accelerate in 2005 and reached the highest level during 2014–2017, with an average annual growth of ~16%. This was probably driven by the ratification of the Kyoto Protocol and the initiation of the Clean Development Mechanism (CDM) and then potentially refuelled by the negotiation and enactment of the Paris Agreement. However, starting in 2017, the number of patented MTAT inventions began to decline and shrunk markedly by 22.8% until 2019.

High-quality MTAT inventions showed sustained growth from 1990 to 2010, with the annual volume enlarging by more than fourfold. As for all patented inventions, the number of high-quality MTAT inventions has increased (accelerated) since 2005 and peaked in 2010. The rapid expansion of high-quality inventions during 2005–2010 might have contributed to the slowdown in global emission growth during 2010–2015. However, the annual application of high-quality MTAT inventions started to fall in 2010, declined by 19.21% during 2010–2015 and plateaued afterward. In pace with the reduced invention scale, the quality of MTAT inventions also declined substantially. The proportion of high-quality inventions among all patented inventions declined by 6.8% annually since 2010 and fluctuated at 11–14% levels in 2017–2019.

Compared to the overall climate change mitigation technologies (CCMTs), MTAT inventions exhibit a substantially slower rate of growth, with high-quality inventions beginning to decline after 2010. Such a gap and the recent decline may be driven by at least three major factors. First, existing climate policies have rarely put methane into regulation[40,41]. After the Kyoto Protocol came into force, many parties announced their commitments on GHG emission mitigations and promulgated plentiful laws, decrees and policies to pursue these goals. However, until recently, most targets and policies focused on CO_2 emissions while seldom targeting CH_4 emissions. As a result of looser regulation strength and weaker policy incentives, the growth of MTAT inventions tended to be slower than that of overall CCMT inventions.

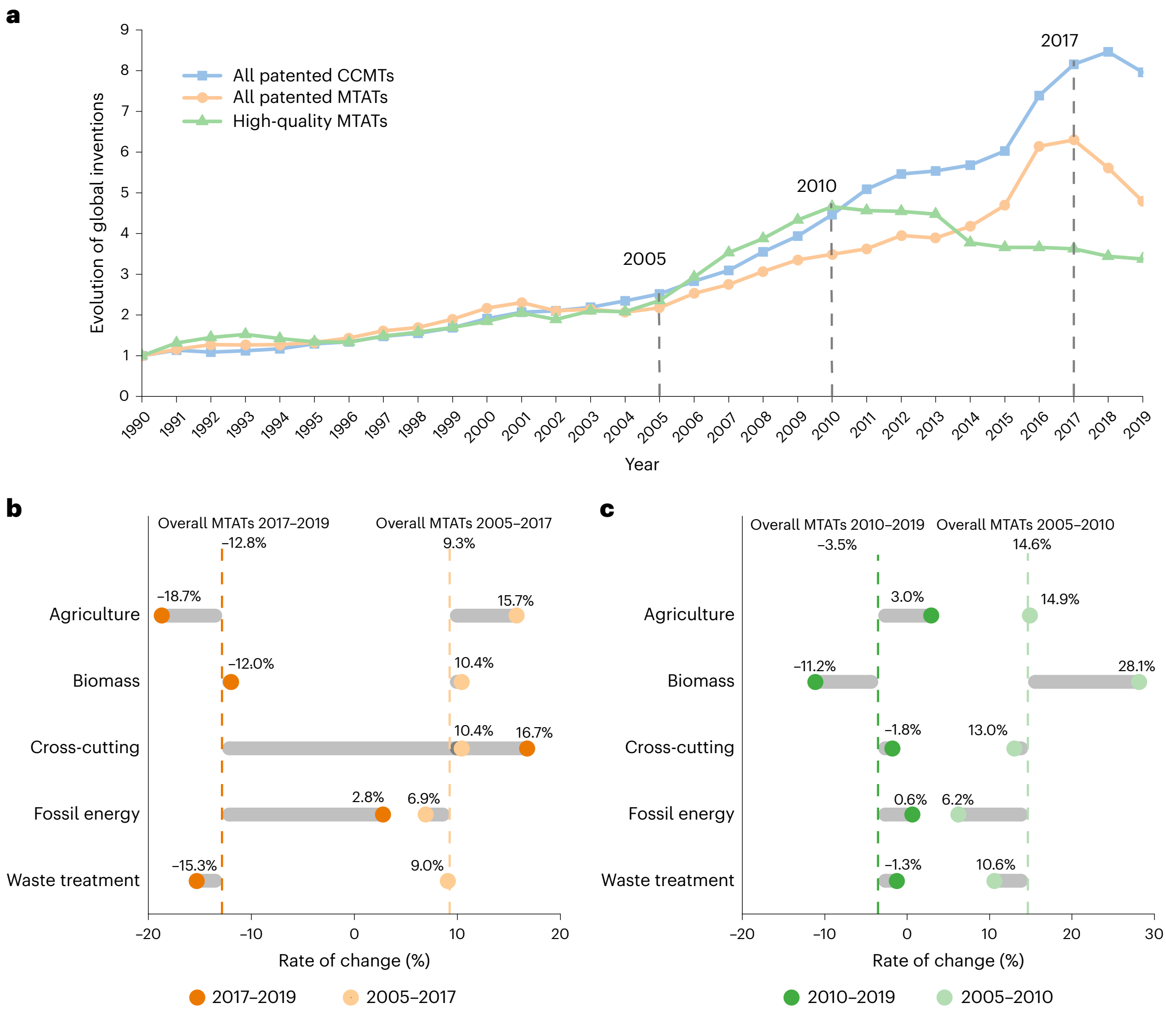

Fig. 1 | Global trend of MTAT inventions. **a**, The evolution of global MTAT inventions relative to 1990. Based on a baseline index of 1 in 1990, the developing trend of all patented and high-quality inventions on MTATs and overall CCMTs from 1990 to 2019 is shown. **b**, The change of all patented MTAT inventions by field. The annual average rate of change in all patented MTAT inventions during the 2005–2017 and 2017–2019 periods is shown, and the inflection point of 2017 is identified by graph analysis and gradient change-point detections. **c**, The change of high-quality MTAT inventions by field. The annual average rate of change in high-quality MTAT inventions during the 2005–2010 and 2010–2019 periods is shown, and the inflection point of 2010 is identified by graph analysis and gradient change-point detections.

Second, the dramatic slump in carbon credit income may have contributed to the recent decline. Profits earned by carbon credits issued from biomass energy, fugitive methane avoidance or landfill gas projects[42] could create strong incentives for MTAT innovative activities. However, affected by the falling international demand for carbon credits from CDM projects, the expected return of methane-based carbon credits plunged dramatically in 2013 (ref. 42), hurting stakeholder motivation for MTAT invention. Finally, technology-specific factors are also involved. The number of patented MTAT inventions in waste treatment and biomass fields decreased rapidly in 2017–2019 (Fig. 1b), which could largely drive a decline in overall MTATs given their dominant proportion. Additionally, after a sharp growth in 2005–2010, high-quality inventions of biomass MTATs exhibited a sizeable decrease after 2010 (Fig. 1c), which might lead to a same-period decline in overall high-quality inventions.

Sectoral distribution and trend of MTAT inventions

Agriculture was the largest source of methane emissions, while accounting for merely 0.7% of global high-quality MTAT inventions in 2017–2019 (Fig. 2a,b). Specifically, enteric fermentation and manure disposal released >32% of global methane emissions, while high-quality inventions on livestock management represented <0.5% of the overall inventions. Rice cultivation generated almost 10% of global emissions, yet related MTAT inventions were incredibly scarce. Such poor performance could hardly provide sufficient technological support for agricultural methane abatement, which calls for both new breakthroughs in agricultural MTATs and ongoing efforts to improve farming practices and dietary behaviours[13,22,32]. Fossil energy was the second largest emitting sector but represented 6.8% of high-quality inventions. In particular, coal mines caused >10% of methane emissions but high-quality inventions in this field were scarce.

In contrast, waste treatment contributed to 66.5% of high-quality MTAT inventions while representing 21.5% of global methane emissions. Although it serves as the largest sectoral driver of MTAT innovation, there are large mismatches between emission sources and emission-reduction technologies within this sector. Particularly, solid waste landfill represented 43.2% of waste-related emissions, yet the high-quality inventions related to this comprised only 0.7% of sectoral total inventions. This mismatch was also detected insides the biomass sector. MTAT inventions in this sector were heavily concentrated on biofuels, with little focus on direct biomass combustion, for example residential biomass used for cooking or warming, which were contrarily the primary sources of sectoral emissions.

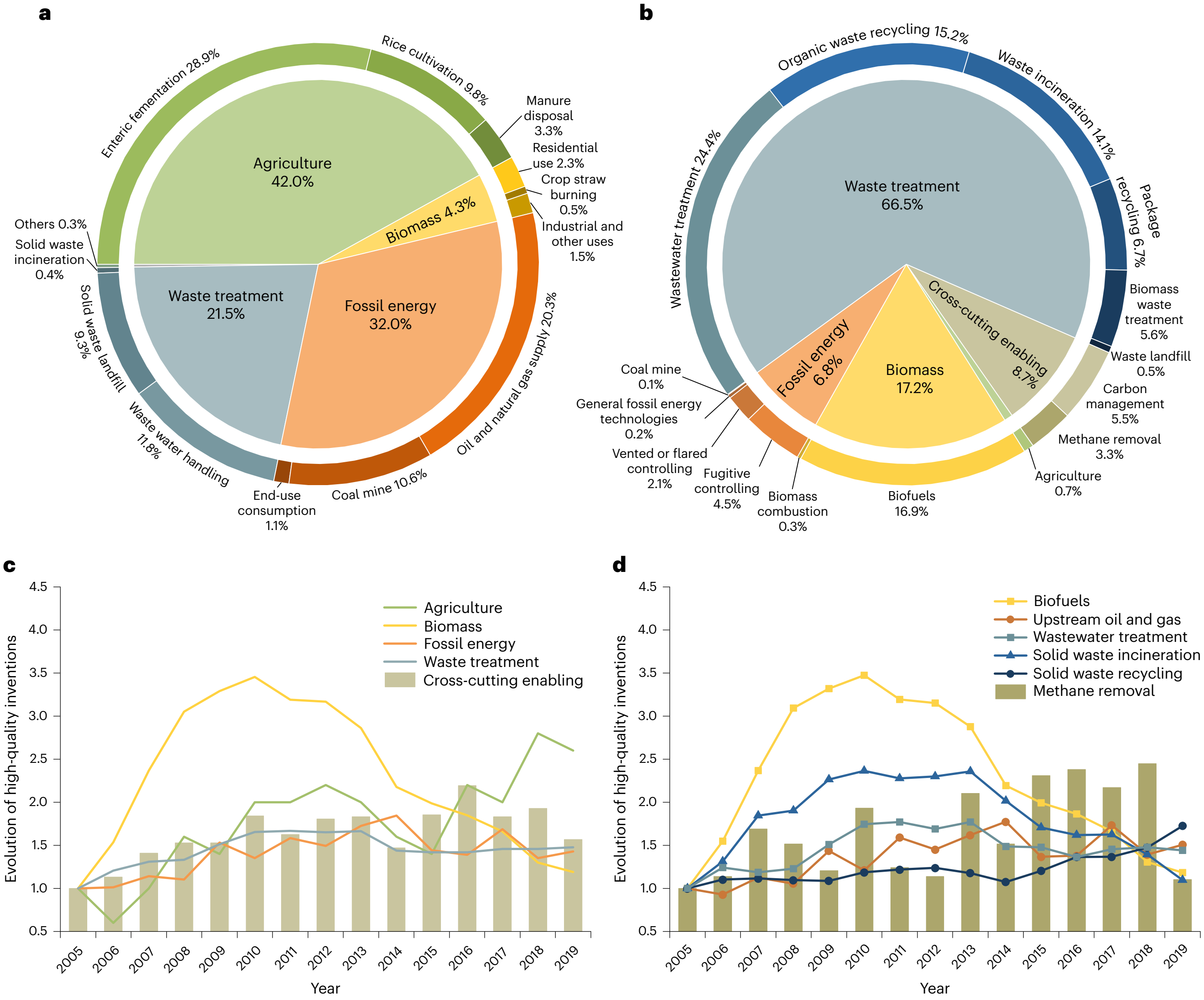

Fig. 2 | Sectoral distribution and developing trend of high-quality MTAT inventions. a,**b**, The sectoral distribution of global methane emissions (**a**) and high-quality MTAT inventions (**b**) in 2017–2019, based on a baseline index of 1 in 2005. **c**,**d**, The developing trends of high-quality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

Beyond that, the developing trend of high-quality MTAT inventions differed by sector (Fig. 2c) and technological subfield (Fig. 2d). Agricultural MTAT inventions followed a fluctuating ascending trend from 2005 to 2015. Probably driven by the recently increasing international concerns for agricultural methane controlling[3,13,22], these inventions showed prominent growths in 2015–2019. However, high-quality inventions remained inadequate, demonstrating massive challenges in agricultural methane governance. MTAT inventions on biomass, particularly biofuels, increased sharply over 2005–2010 but, afterwards, they presented a downtrend probably due to the bottleneck encountered after growing technological maturity and the intense disputes about large-scale bioenergy deployment[43,44]. Besides, we observed sustained growth in fossil energy MTAT inventions during 2005–2014 but an obvious decline in 2015–2016. This decline, probably driven by drops in oil and carbon prices, was also detected by studies on low-carbon energy technologies[25,28,45]. Consistent with an updated study[28], we noticed that fossil energy inventions resumed growth in 2017 with increasingly stringent regulations on methane from oil and gas supply[15,16].

For the waste treatment sector, MTAT inventions increased steadily until 2013, declined obviously in 2014 and plateaued afterwards. A similar trend was observed in the technological subfield of wastewater treatment but not in solid waste treatment. Specifically, solid waste incineration MTATs increased faster than the sectoral average before 2013 but thereafter began to decrease; in contrast, solid waste recycling MTATs rose slowly at first but their growth started to accelerate in recent years. In view of the high cost-efficiency of technologies such as waste separation and direct reuse, solid waste recycling MTATs might unleash great potentials in the future[13,17]. In addition, cross-cutting enabling MTATs experienced general growth by 2013, an apparent decline in 2014 and then a rapid recovery. Noticeably, the inventions relating to atmospheric methane removal have featured both high quality and remarkable advances since 2015, implying an emerging hotspot for methane control.

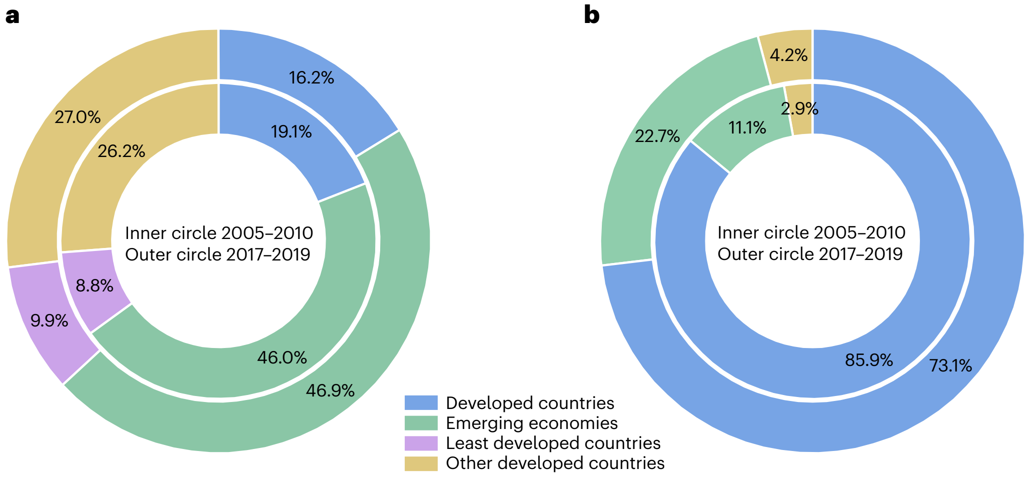

Fig. 3 | Distribution of methane emissions and high-quality MTAT inventions by country group. a, The percentage of four country groups in global methane emissions in the 2005–2010 and 2017–2019 periods. **b**, The percentage of three country groups in global high-quality MTAT inventions as the group of LDCs holds no high-quality inventions in both periods. The 2005–2010 period is selected to represent an accelerated growth stage in MTAT inventions, while the 2017–2019 period represents the recent declining period. Numbers may not sum to 100% due to rounding.

National-level MTAT inventions and methane emissions

To capture the national-level distribution by development levels in more detail, we grouped developing countries into emerging economies[46], least developed countries (LDCs)[47] and other developing countries (Supplementary Note 1). Our results reveal that developing countries and particularly emerging economies were increasingly dominant in global methane emissions but >70% of high-quality MTAT inventions were mastered by developed countries (Fig. 3).

Specifically, high-quality inventions were heavily concentrated in a few developed countries, except for China and South Korea (South Korea's classification was changed in 2021; Supplementary Note 1) (Fig. 4). The United States, Japan, Germany, France, Canada and the United Kingdom have long been the powerhouses in high-quality MTAT inventions, jointly contributing to 54.2% of the global totals. Beyond them, another six developed countries enlisted themselves in the top 15 innovators. However, except for the United States and Australia, no other developed countries could be considered as large emitters and, probably attributed to their leading role in MTAT invention, most of these countries showed decline or decelerated growth in emissions.

Emerging economies accounted for 46.8% of global methane emissions and 50.4% of emission growth relative to 2005–2010 but their catch-up in MTAT invention lagged far behind. Except for the United States, all the largest five emitters were emerging economies. Mexico and Argentina also ranked among the top 15 emitters. However, apart from China and South Korea, high-quality inventions were rarely observed there. China and South Korea have entered high-quality innovator clubs and performed much better in terms of all patented inventions (Extended Data Fig. 1). This implies that, although they have been catching up, a major portion of their inventions were of poor quality. Additionally, we should note that LDCs played an increasing role in methane, and particularly agricultural methane, governance. They accounted for 42.2% of global growths in agricultural methane emissions relative to 2005–2010 and would continue to be the principal drivers[13], whereas they held neither high-quality nor domestically patented agricultural MTAT inventions.

Moreover, the national-level distribution of MTAT inventions varies by technical field. Relative to overall inventions, Japan, Germany, Israel, Singapore and Switzerland performed better in terms of fossil energy MTAT inventions (Extended Data Fig. 2). A few large energy-importing countries have owned 61.1% of high-quality fossil energy inventions but accounted for only 1.0% of related emissions. In contrast, the member states of the Organization of Petroleum Exporting Countries (OPEC/OPEC+) generated more than half of global methane emissions from upstream oil and gas supply and were predicted to remain the leading drivers[48,49] but none of them has created adequate inventions. Additionally, eight large Asian coal-producing countries accounted for 76.5% of global coal mine methane emissions. However, except for China, none of them owned high-quality inventions on coal mine MTATs; and, even in China, no noticeable progress in related inventions was detected.

In the waste treatment field, ~70% of high-quality MTAT inventions were held by developed countries, while the waste-related emissions were increasingly centred in populous developing countries (Extended Data Fig. 3). Twelve developing countries with populations of >100 million have jointly represented 52.8% of global waste-related emissions and 75.5% of emission growths relative to 2005–2010. However, except for China, other countries barely owned high-quality inventions on waste treatment. Considering the expanding population and associated waste generation, these countries might keep being major growth sources of waste-related emissions[13,18] and are thus in urgent need of advanced waste treatment MTATs.

International transfer and diffusion of MTATs

Given the serious mismatches between MTAT inventions and emissions, international transfer serves as a vital channel for high-emission and technology-hungry countries to acquire advanced technologies and cash them to realistic methane abatements[50–52]. However, international transfers of MTATs have been highly concentrated in developed countries and emerging economies (Fig. 5a). Developed countries contributed to 85.7% of MTAT transfers-out, of which the United States, Japan, Germany and France were the top four transferors. Emerging economies are increasingly active in international transfers, not only becoming major technology receivers but also contributing to >10% of global total outflows. However, most of these transfers occurred in China, South Korea and Brazil. Russia and Mexico also acted actively to introduce MTATs, whereas this was not the case for other emerging economies. Additionally, it should be noted that LDCs stayed away from MTAT innovative activities by neither inventing domestically nor importing related technologies.

Moreover, we noticed an obvious lower diffusion rate of MTATs relative to the overall CCMTs (Fig. 5b). Defined as the ratio between

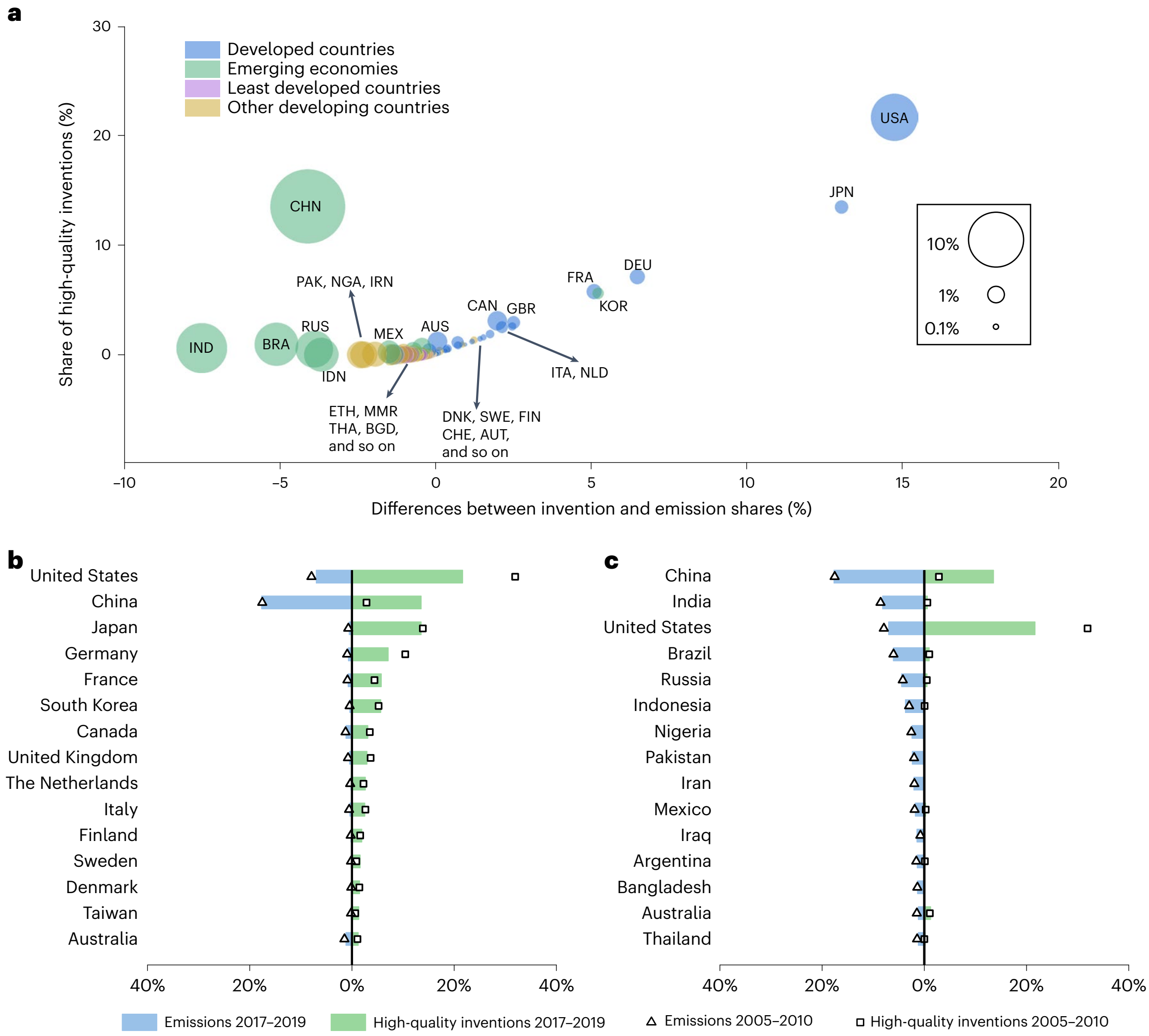

Fig. 4 | National-level distribution of methane emissions and high-quality MTAT inventions. a, The mismatched distributions of methane emissions and high-quality MTAT inventions across countries or regions in 2017–2019; circle areas represent the scale of national emissions, the abbreviations represent codes for countries or regions in the ISO 3166-1 Alpha-3 Country Code list and the differences between invention and emission shares are calculated by subtracting the percentage of national emissions from that of national high-quality MTAT inventions. **b**,**c**, The proportion of the top 15 inventing (**b**) and emitting (**c**) countries in global high-quality MTAT inventions and methane emissions in the 2005–2010 and 2017–2019 periods. Taiwan refers to the Taiwan province of China.

international invention transfers to all patented inventions, the diffusion rate of MTATs was 11.1% lower than the average diffusion rate of CCMTs during 2017–2019 and this gap widened from 2005 to 2019. The poorer diffusion level highlighted a less active international technology market for MTATs relative to other types of CCMTs, such as energy efficiency, clean energy and electric vehicle technologies[25,28,45], calling for increasing attention to international trading and promotion of MTATs.

Additionally, international MTAT diffusions vary largely across technology fields. The diffusion levels of fossil energy and biomass MTATs were markedly greater than those of overall MTATs, behind which technology cost-effectiveness in these two fields and multinational energy enterprise might make major contributions. Cross-cutting enabling MTATs also presented a higher diffusion rate, which reflected the recently increasing international attentions on negative emission technologies. In contrast, for reasons including but not limited to agroecological and agronomic constraints, dysfunctional agricultural input markets and poor financial accesses for smallholder farmers[53–55], agricultural MTATs demonstrated a particularly lower rate of international diffusion, which further worsened the worrisome picture of agricultural MTATs. In addition, despite having the largest invention scale, waste treatment MTATs lacked vitality in international diffusion. High infrastructure or equipment investments required by waste incineration and wastewater treatment technologies[13] might help explain this phenomenon.

Discussion and policy implications

Our analysis shows that global high-quality MTAT inventions experienced an accelerated growth in 2005–2010, which possibly contributed to the slowdown in methane emission growths in 2010–2015 (Extended Data Fig. 4). However, starting from 2010, high-quality MTAT inventions present a worrisome declining trend. Our analysis also reveals the increasing mismatches between countries dominating MTAT inventions and those driving up global emissions. Spurred by early-bird climate legislations and constantly improved policy efforts[56–58], a few developed countries have made considerable progress in MTAT invention. Accompanying this, methane emissions in these leading innovating countries have begun to decline or slow down, with most of future growths coming from elsewhere. This mismatch makes it harder to translate MTAT inventions into tangible methane reductions. International transfer can facilitate this translation but current MTAT

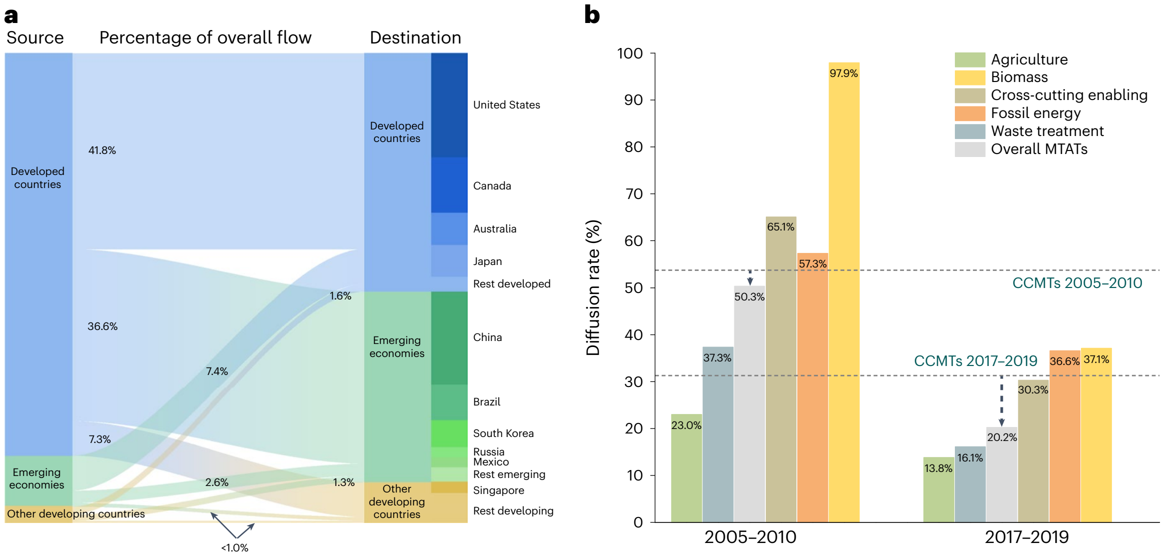

Fig. 5 | International transfer and diffusion of MTATs. a, The geographical distribution of MTAT international transfers by country group in 2017–2019 and the countries listed on the right of the Sankey diagram represent the top receiving countries of MTATs in their respective country groups. **b**, The diffusion rate of MTATs by technology field during 2005–2010 and 2017–2019, in which the two dashed lines show that of overall CCMTs.

transfers are not active and highly concentrate in developed countries and several emerging economies.

Against this background, our study provides several important insights. First, accelerating technological catch-up in emerging economies is critical. Emerging economies are likely to keep being the top source of global methane emissions[59–61] but their catch-up in MTATs lags behind. Driven by both powerful incentives on innovation and ambitious policies on climate governance[58,62,63], China and South Korea have achieved substantial catch-up in MTAT invention. However, no obvious progress has occurred in other emerging economies. Second, there is an urgent need to provide LDCs with technical assistance. Given their tiny portion in GHGs emissions[64], LDCs are rarely underlined in global carbon reduction. Yet, we cannot ignore their position in global methane governance[13,21]. The assistance of negative or low-cost MTATs in agricultural and waste treatment fields, such as technologies relating to improved farming practice and waste recycling[17,20–22], should be a priority in international technology facilities[65,66].

Finally, it is imperative to better motivate MTAT invention and diffusion. Expected high return is a core motive for innovation[67]. Hence, both the increasingly stringent regulation of multitype methane emissions and the serious cogitation of carbon credit incentive in the upcoming international carbon market[68] are highlighted for raising the expected return of MTAT invention. Meanwhile, market-based, government-guided, international cooperative and social supporting modes should complement each other to facilitate MTAT diffusion, together with critical discussions about the applicability of intellectual property rights flexibilities to climate-friendly technologies[55,69,70]. Furthermore, sector- and region-specific strategies are also underscored, including promoting the application of fossil energy MTATs in OPEC/OPEC+ and Asian large coal-producing countries, facilitating the transfer of low-cost high-adaptable waste treatment MTATs to populous developing countries and attaching importance to cross-cutting enabling MTATs.

This study has several limitations. Although patent has been widely used to measure innovation, this indicator is not flawless[71,72]. Given the immature patent system and incomplete data coverage in less developed countries, their inventions on MTATs may be underestimated. Additionally, compared with other technological fields, the agricultural field is usually less patent-preferred and less active in diffusion[71,73], which may affect agricultural MTAT analysis. Besides, while a slowdown in methane emission growth has occurred following the rapid growth of MTAT inventions, we do not engage in a causality analysis. We also notice varying trends in MTAT inventions across countries but do not dissect the underlying reason. Hence, how much MTAT inventions contribute to reducing methane emissions and whether policy efforts affect national MTAT inventions are of interest to our future research.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-01947-x.

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Methods

Data

Patent data. To measure the global trend in invention and diffusion of MTATs, we relied on patent data from the Worldwide Patent Statistical Database PATSTAT (2022, Spring version), which is maintained by the EPO. Considering that up to 30 months is needed for an international patent from its initial application to subsequent filings in other nations and that the coverage rate of the latest data varies greatly across patent offices, we excluded patent data after 2019 and included records from 1990 to 2019. Additionally, we applied PFs as the metric unit of innovation output and we used IPFs filed in at least two jurisdictions as a proxy for high-quality inventions. IPFs can address two inborn defects in patent data: (1) the propensity to patent and the individual value of patent are highly heterogeneous and adopting IPFs rather than patent counts can help to avoid these shortcomings; and (2) given that important information, such as the countries of applicants or inventors, is often missing for patents from less developed economies, we can impute these data on the basis of the information available within the same patent family[74,75].

Moreover, we focused on the IPFs in type of invention and incorporated all patent applications, regardless of whether they were granted or not, into analysis. We adopted the earliest filing date as the invention date of a given patent family. Additionally, following the practice of the World Intellectual Property Organization (WIPO), we adopted the country of the first applicant, rather than that of the inventors, as the origin of a given patent family[76,77]. This approach was based on two considerations: (1) we were interested in the ownership and the factual possibility of applying technologies, rather than tracing where an invention was created; and (2) the PATSTAT coverage of the country codes of inventors outside Europe and the United States was far from ideal[78] and notably lower than that of the country codes of applicants[79].

To fill in the missing country origin for a patent, first, we imputed it on the basis of the earliest patent record on the applicant's country information available within the patent family. Second, we filled in the missing data with linked original patent data from patent offices, such as the China National Intellectual Property Administration, the Japan Patent Office, the United States Patent and Trademark Office and the WIPO[74,75]. Otherwise, if the applicant's country information could not be obtained via the abovementioned steps, we supplemented them with available data from the earliest patent's inventor in sequence. Finally, we filled in all other missing country origins with the location of the patent office where the patent was filed for the first time.

Methane emissions data. Methane emission data were collected from the Emissions Database for Global Atmospheric Research (EDGAR) Community GHG Database v.7.0 (a collaboration between the European Commission, Joint Research Centre and International Energy Agency) at https://edgar.jrc.ec.europa.eu/dataset_ghg70. The database covers yearly methane emissions by country or dependent territory originating from major emitting sources, such as rice cultivation, enteric fermentation, manure disposal, coal mine, upstream oil and natural gas, wastewater treatment, solid waste treatment, incomplete biomass burning and industrial processes[80]. Here, we focused on four chief categories of emission sources, namely agriculture, fossil energy, waste treatment and biomass, jointly accounting for >95% of global anthropogenic methane emissions.

Identification and mapping strategy for MTATs

On the basis of the EPO Y02 scheme and the potential methane abatement pathways and measures reported in recent literature and proposed by industrial experts and related scholars, we developed a five-step search and mapping method for MTAT patents. The Y02 scheme was customized by the EPO for climate change mitigation and adaptation technologies, which facilitates a more convenient retrieval of patent documents relating to these technologies. The EPO Y02 scheme contains eight sections. Except for the Y02A which represents climate change adaptation technologies, the remaining seven sections of Y02B, Y02C, Y02D, Y02E, Y02P, Y02T and Y02W refer to CCMTs in the fields of building, GHG capture and storage, information and communication, energy production and supply, industry and agriculture, transportation, waste and wastewater, respectively[81]. We excluded the Y02A section and restricted our search to seven CCMT-related sections. In addition, while CCMTs cover emission reduction, capture, storage or removal technologies for all types of GHGs, our focus of this study was methane-targeted technologies tailored to decreasing methane emissions or increasing methane removal. Other technologies that aim at curbing the emissions of CO_2 or other types of GHGs but with methane abatement cobenefits were excluded, such as photovoltaic and wind power technologies.

To ensure the identification and classification of MTAT inventions as accurately as possible, we constructed a set of search code lists by integrating the Cooperative Patent Classification (CPC) codes of the EPO Y02 scheme with the potential methane abatement pathways and measures, International Patent Classification (IPC) codes and a series of keywords to search across the titles and abstracts of PFs based on the advice of patent examiners, scholars and industrial experts in methane-related technologies. The more detailed procedures for mapping and classifying MTAT PFs were as follows:

- Establish the CPC code list for MTAT PFs. On the basis of the description of the Y02 classification scheme, the CPC codes under this scheme were matched to methane-reduction pathways and measures reported in recent literature and proposed by industrial experts and related scholars to form a specific list of CPC codes for MATA inventions in the agricultural, fossil energy, waste treatment, biomass and cross-cutting enabling fields.
- Identify MTAT PFs in 12 subfields solely with the established CPC codes. There are 12 subfields of MTAT PFs that can be suitably matched with the CPC codes: rice cultivation, land use management, afforestation and reforestation, livestock management (part), wastewater treatment, waste landfill, waste incineration (part), biomass waste treatment, packaging waste recycling, organic waste recycling, biofuels and carbon pricing and management. MTAT PFs in these subfields were identified solely with CPC codes through this step.
- Extract MTAT PFs in three subfields on the basis of the conjunction of CPC codes with IPC codes or specific keyword. Some MTAT PFs relating to livestock management, waste incineration and biomass combustion cannot be identified solely relying on CPC codes. Hence, in this step, we applied the conjunction of CPC and IPC codes to identify MTAT inventions for livestock management. Similarly, MTAT inventions falling into waste incineration and biomass combustion subfields were identified by searching with both CPC codes and the specific keyword 'biomass'.
- Screen MTAT PFs in five subfields by integrating CPC codes, IPC codes and keyword sets. MTAT PFs relating to fossil energy and atmospheric methane removal cannot be filtered out through the abovementioned procedures. Hence, on the basis of the technical proposals and toolkits of authoritative organizations and relevant studies[82,83], we developed several sets of keywords to identify MTAT PFs in these two categories. Specifically, the following was adopted:
    - The codes 'Y02C20/20 while not belonging to IPC class A' and 'Y02E' were combined with keywords such as 'coal mine', 'coalbed', 'coal well', 'coal methane', 'coal extraction', 'coal dressing' and 'CMM' and 'mine gas', to identify MTAT PFs falling into the subfield of coal mine.
    - The codes 'Y02C20/20 while not belonging to IPC class A' and 'Y02E' were combined with keywords such as 'fugitive emission',

'leak', 'LDAR', 'monitor', 'detect', 'sensor', 'sensing', 'satellite', 'aircraft', 'aerobat' and 'infrared camera', to identify MTAT PFs for the subfield of fugitive emission controlling in oil and gas supply.
  - The codes 'Y02C20/20 while not belonging to IPC class A' and 'Y02E' were combined with keywords such as 'vented emission', 'flared emission', 'pneumatic device', 'pneumatic controller', 'pneumatic pump', 'electrical pump', 'valve', 'compressor seal', 'valve rod', 'electric motor', 'instrument air system', 'vapour recovery unit', 'blowdown', 'flare', 'flaring', 'plunger' and 'liquid unload', to identify MTAT PFs falling under the subfield of vented or flared emission controlling in oil and gas supply.
  - The codes 'Y02C20/20 while not belonging to IPC class A' and 'Y02E' were combined with keywords such as 'methane-reduced catalyst', 'methane catalysator', 'microturbine', 'pipeline pump-down' and 'green completion', to identify MTAT PFs belonging to the subfield of general fossil energy technologies.
  - After this, MTAT PFs belonging to the subfield of atmospheric methane removal were obtained by combining two groups of data. One group was the remaining instances of the Y02C20/20 after excluding those belonging to IPC class A and those classified into fossil energy fields. Here, we need to specify that, although the CPC code Y02C20/20 refers to patents for methane capture or disposal, it does not differentiate those for point sources from those for direct atmospheric removal. In this study, we subdivided PFs in the Y02C20/20 class into three subcategories—methane capture or disposal for livestock, for fossil energy and direct air removal. In addition, the other group integrated the Y02C code with keyword sets such as {direct air capture, direct atmospheric capture, methane removal, methane conversion, methane oxidation, negative emission, NET, zeolite, porous polymer network, methane adsorbent, metal-organic framework, iron-salt aerosol or catalytic paint}, to search for the possible omissions of atmospheric methane removal patents not belonging to Y02C20/20 but falling into the Y02C category.
- Filter out false positives in the identified fossil energy MTAT PFs with keyword sets and manual checks. There are several discernable false positives in fossil energy MTAT patents identified above, as some terms used in the fourth step such as 'leak', 'detect' and 'sensing', also frequently appear in patent texts for nuclear, battery or energy storage technologies. Hence, in the last step, we excluded patents containing the keywords such as 'unclear', 'battery', 'lithium cell', 'fuel cell', 'grid', 'energy storage', 'power generation' and 'power transmission', from the identified PFs on fossil energy MTATs. After that, we also manually checked the titles and abstracts of these patents to further filter out false positives. Overall, ~16,000 noise PFs were screened out through this step.

The technological fields and subfields, CPC and IPC codes and keyword lists used for MTAT identification are summarized in Supplementary Table 1. In total, 175,963 unique invention PFs on MTATs were obtained during the 1990–2019 period, 32,616 of which were rated as high-quality international patent families.

Measuring the international transfer and diffusion of MTAT inventions

As patenting overseas is costly, applicants simply patent an invention in foreign countries or regions when they plan to market it there. Therefore, following the existing literature and common practices[77], we adopted the number of times of subsequent filings of an IPF in countries or regions outside its originating country to measure MTAT cross-country transfers. The country (or region) of the earliest filing of a given IPF was identified as the originating country of MTAT transfer, while the countries of patent offices where subsequent filings were sent to were regarded as the receiving countries. As an illustration, for an IPF which received its earliest filing in the United States and was subsequently filed in China, Japan and Germany, the number of international transfers was determined as three and the United State was identified as the originating country of this transfer, with China, Japan and Germany being the three receiving countries. Additionally, we clarified that we excluded some internationally transferred inventions filed at international or regional patent offices, such as the WIPO or the EPO, as they could not be assigned to a specific country or dependent territory[77,84]. Overall, we developed a panel dataset for MTAT international transfer that involved 131 originating and 83 receiving countries or dependent territories during the studied period of 1990–2019.

On this basis, we defined the diffusion rate of MTAT invention as the ratio between the number of international transfers and the number of total patented inventions. For a specific technology field of MTATs, for instance agricultural MTATs, the diffusion rate for 2017–2019 could be calculated as the ratio of the number of cross-country transfers of agricultural MTAT inventions to that of all patented agricultural inventions during this period. Regarding the overall MTATs, the diffusion rate was measured by the ratio of the number of cross-country invention transfers to the number of all patented MTAT inventions.

Robustness test

The robustness of the major findings was assessed by two methods. We used the MTAT PFs whose first filings were granted to rerun the analyses, results of which (Supplementary Figs. 1–3) were highly consistent with those obtained by applications of PFs, regardless of whether the filings were granted or not, in the main text. In addition, we applied the top 10% highly cited PFs within each technological field as a proxy for high-quality inventions, which also generated essentially consistent results (Supplementary Figs. 4–6). A more detailed analysis of the robustness tests is presented in Supplementary Note 2.

Uncertainty analysis

The uncertainties in this study originate from two major sources, namely, uncertainties in patent data and selection criteria and uncertainties in methane emission estimates. The detailed uncertainty analysis is presented in Supplementary Note 3.

Data availability

MTAT invention, transfer and diffusion data as well as methane emission data used in the study are available at https://zenodo.org/records/10531178. Methane emission data were collected from the EDGAR Community GHG Database v.7.0, available at https://edgar.jrc.ec.europa.eu/dataset_ghg70.

Code availability

The detailed searching and programming codes used by this study have been uploaded to GitHub (https://github.com/DeyunYinWIPO/global_methane)[85].

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Acknowledgements

We appreciate the support from the National Social Science Foundation of China (grant no. 21CGL036, J.J.), the National Natural Science Foundation of China (grant no. 72173058, B.Y.), the Natural Science Foundation of Guangdong Province (grant no. 2022A1515011075, J.J.), the Special Foundation for Sustainable Development Research of Shenzhen (grant no. KCXST20221021111405012, J.J.), the Shenzhen's Peacock Program (grant no. ZX20210426, D.Y.) and the US Department of Energy (grant no. DE-AC02-05CH11231, N.Z.).

Author contributions

J.J. and D.Y. designed the study and performed patent identification and classification. J.J., D.Y., Z.S., B.Y. and N.Z. analysed the data and contributed to discussions. J.J. and Z.S. performed data curation and graphics drawing. All authors wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-024-01947-x.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-024-01947-x.

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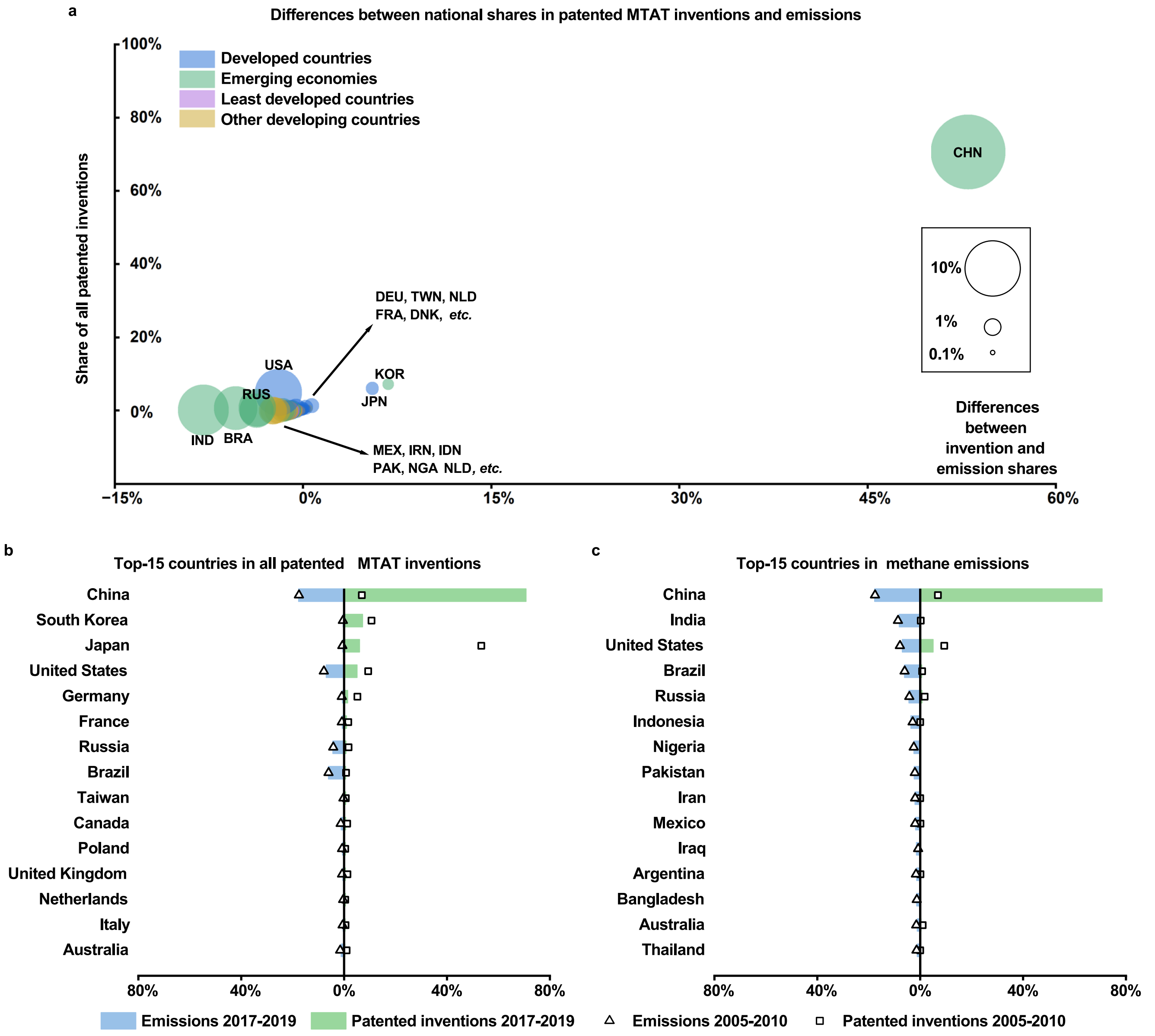
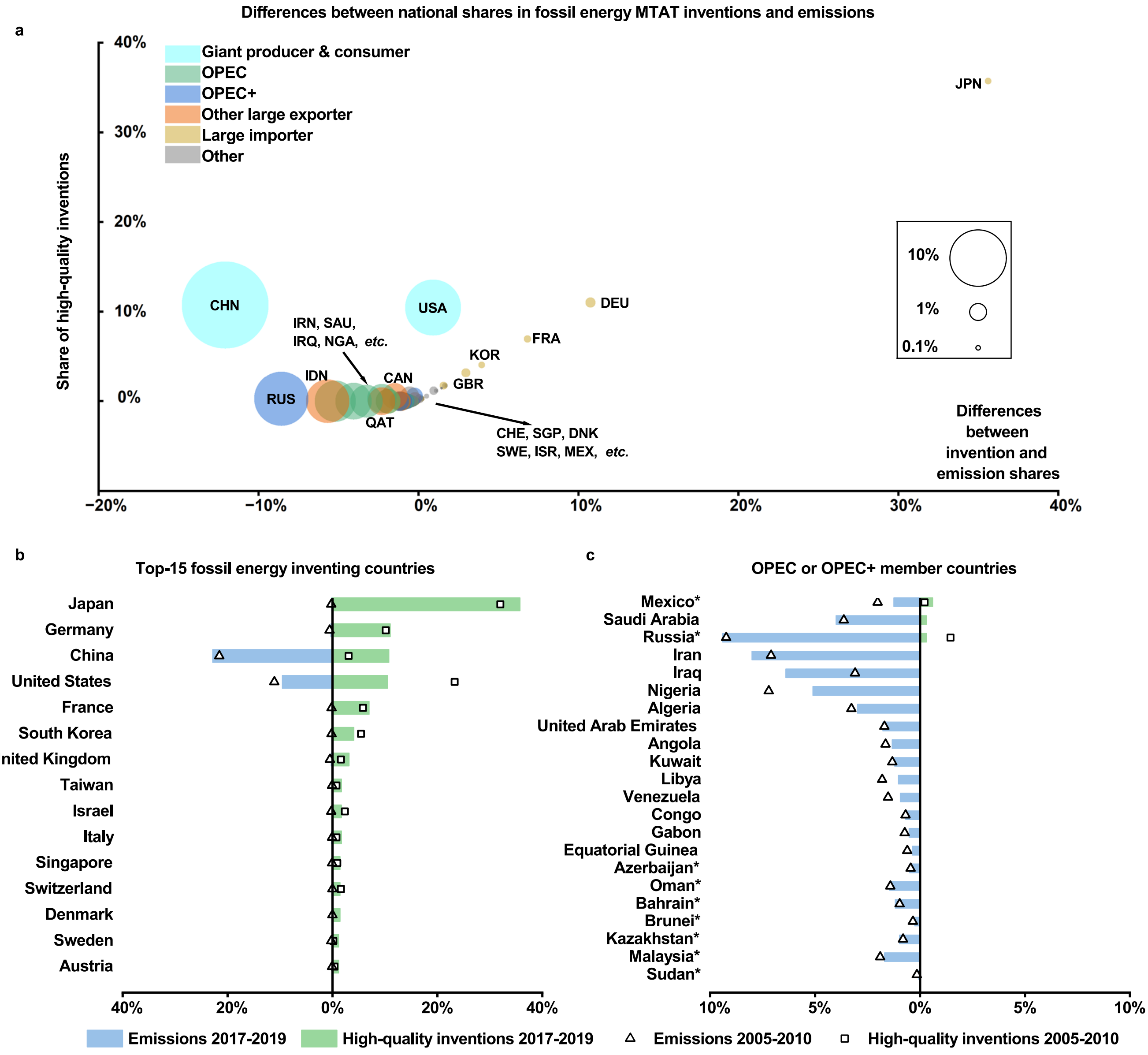
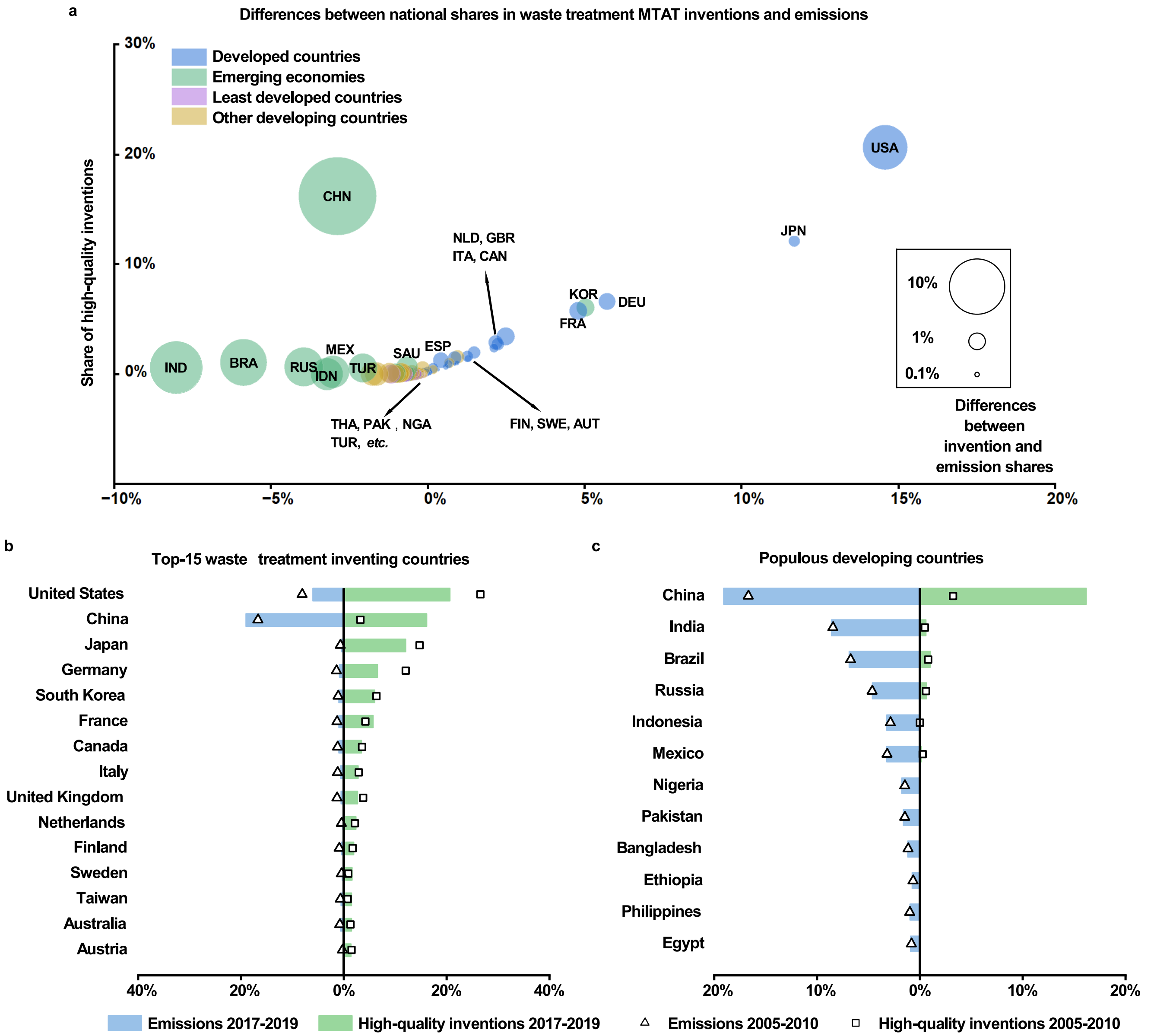
Peer review information *Nature Climate Change* thanks Fang Zhang and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.



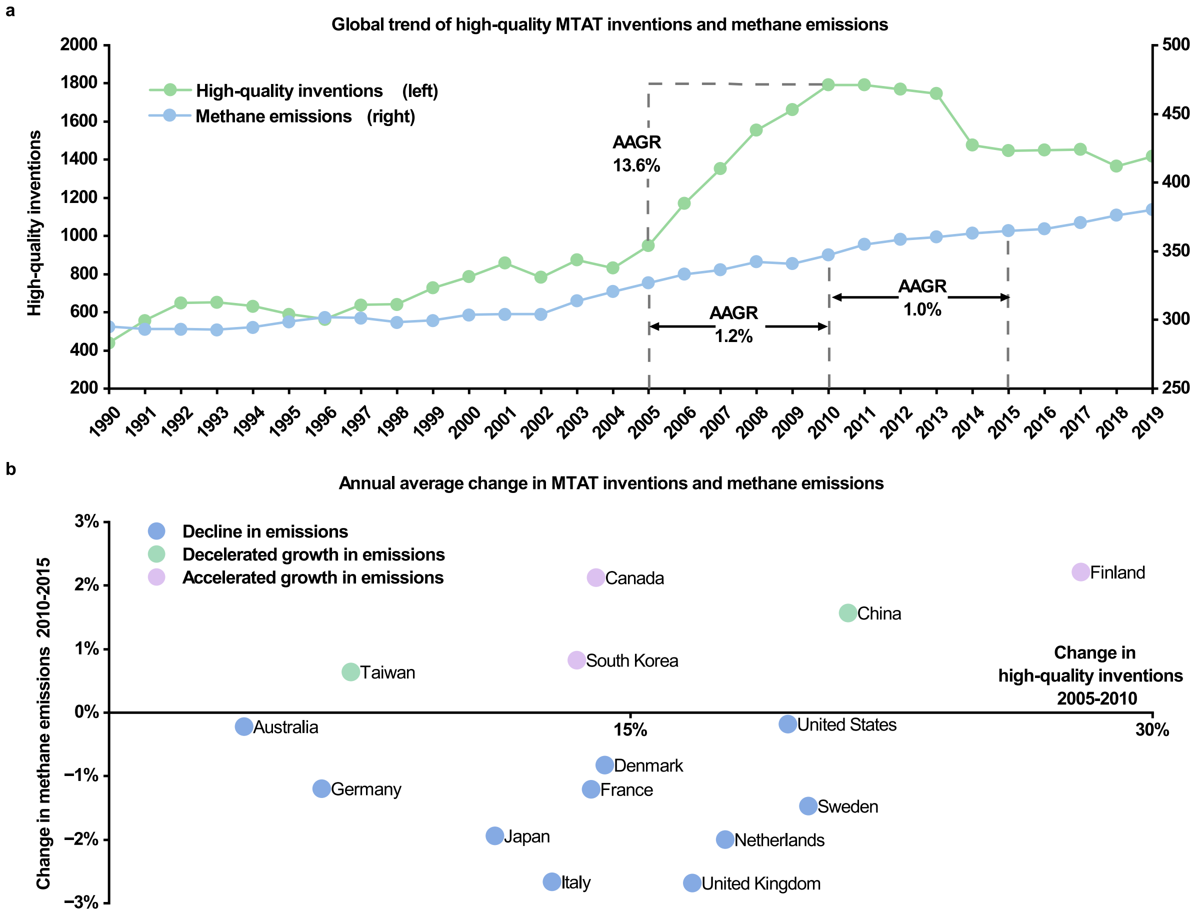
Extended Data Fig. 1 | National-level distribution of all patented MTAT inventions and methane emissions. **a** presents the mismatched distribution of all patented MTAT inventions and methane emissions across countries or regions during 2017–2019, where the circle areas represent the scale of national emissions, and the differences between invention and emission shares are calculated by subtracting the percentage of national emissions from that of national patented inventions; while **b** and **c** show the proportion of the top 15 inventing and emitting countries in global patented MTAT inventions and methane emissions during the 2005–2010 and 2017–2019 periods, respectively. The period of 2005–2010 is selected to capture an accelerated growth stage in MTAT inventions, while 2017–2019 representing a recent declining period. Taiwan refers to the Taiwan province of China.



Extended Data Fig. 2 | National-level distribution of high-quality fossil energy MTAT inventions and methane emissions. a shows the mismatched distribution of high-quality fossil energy MTAT inventions and methane emissions across countries or regions in 2017–2019, where the circle areas represent the scale of national fossil energy methane emissions, and the differences between invention and emission shares are calculated by subtracting the percentage of national fossil energy emissions from that of national high-quality fossil energy inventions; while **b** and **c** present the proportion of the top-15 fossil energy inventing countries and the OPEC/OPEC+ member countries in global overall inventions and emissions in the 2005–2010 and 2017–2019 periods, respectively. Taiwan refers to the Taiwan province of China and the asterisk denotes OPEC+ member states.



Extended Data Fig. 3 | National-level distribution of high-quality waste treatment MTAT inventions and methane emissions. a presents the mismatched distribution of high-quality waste treatment MTAT inventions and methane emissions across countries or regions in 2017–2019, where the circle areas represent the scale of national waste-related methane emissions, and the differences between invention and emission shares are calculated by subtracting the percentage of national waste-related emissions from that of national high-quality waste treatment inventions; and **b** and **c** show the proportion of the top-15 waste treatment inventing countries and the populous developing countries in global waste treatment MTAT inventions and related emissions in the 2005–2010 and 2017–2019 periods, respectively. Taiwan refers to the Taiwan province of China and the populous developing countries are selected based on a population of more than 100 million.



Extended Data Fig. 4 | Changing trend of high-quality MTAT inventions and methane emissions. a shows the changing trend of global high-quality MTAT inventions and methane emissions from 1990 to 2019, with AAGR representing the annual average growth rate; and **b** presents the relationship between the change in 2005–2010 high-quality inventions and that in 2010–2015 methane emissions of the top-15 inventing countries or regions. Taiwan represents the Taiwan province of China.