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Environmental Finance: An Interdisciplinary Review

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ABSTRACT

Environmental finance has gained considerable attention globally as an emerging interdisciplinary research area. This study uses bibliometric analysis to systematically review major studies on environmental finance-related areas published since the 1970s. Through a bibliometric analysis of 892 environmental finance-related articles sourced from the Web of Science database, we identified the main research streams and illustrated the trending research themes of environmental finance. We find that publications related to environmental finance have increased exponentially over the past decade. Current research streams include corporate and social responsibility (CSR), climate negotiations, natural gas price volatility, national policy, and cost comparisons. Further analysis of the recent five years of literature shows that emerging research topics include climate finance, sustainable finance, firm value, climate risk, and green bonds. Finally, we conclude with a future research agenda for environmental finance.

1. Introduction

Rapid industrial growth poses significant environmental challenges, such as rising pollution (Lee and Chang, 2008; Shahbaz et al., 2013) and resource depletion (Jayanthakumaran et al., 2012; Hanif, 2018). Environmental issues have become major threats to human health, survival, and development (Settele et al., 2020; Klenert et al., 2020; Sharma et al., 2021). Sustainable development and green recovery have become a common goal sought by countries globally to alleviate the conflict between economic growth and environmental protection (Tian et al., 2022; Zhao et al., 2022). Countries worldwide have pledged to reduce their carbon emissions in response to climate change. For example, China pledged in September 2020 to peak carbon emissions by 2030 and to achieve carbon neutrality by 2060[1]; the United States committed to reducing emissions by 50-52% by 2030 compared to 2005 and achieving net-zero emissions by 2050 at the Leaders Summit on Climate in April 2021; Canada committed to reducing emissions by 40-45% by 2030 compared to 2005; Japan committed to reducing emissions by 46% by 2030 compared to 2013; the United Kingdom committed to reducing emissions by 78% by 2035 compared to 1990; and Brazil committed to achieving carbon neutrality by 2050[2]. There has been an urgent call for countries to achieve economic transformation (Fu, 2020; Song et al., 2020b; Guo et al., 2021), sustainable development (Danso et al., 2020; Kim and Lee, 2020), and energy transition (Nelson and Allwood, 2021; Kang et al., 2022).

However, substantial environmental improvement cannot be achieved without sufficient financial support (Elheddad et al., 2021). In other words, environmental protection should progress in a financially friendly way, co-developing with financial instruments. Consider the planetary boundaries as an example. The nine environmental boundaries are essential earth "life support systems" for human survival (Rockström et al., 2009), including climate change, biosphere integrity,

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[1] Chinese president declared at the 75th General Debate of the United Nations General Assembly.
[2] https://earth.org/leaders-summit-on-climate-2021-a-summary/

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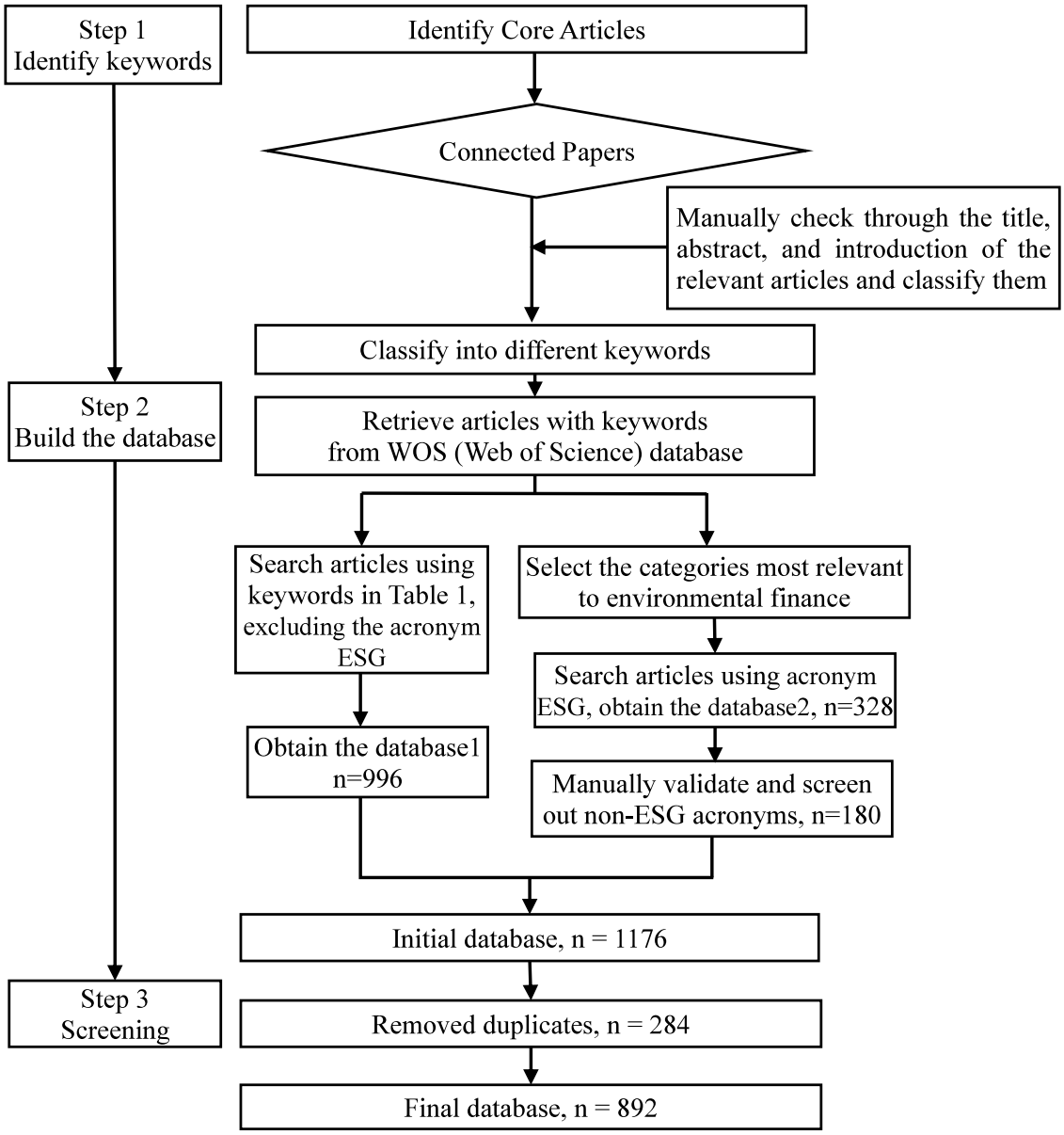

Fig. 1. Literature screening process

land system change, freshwater use, biochemical flows, ocean acidification, atmospheric aerosol loading, ozone depletion, and novel entities. None of the nine environmental boundaries can be mitigated or solved without a huge financial budget. Worryingly, countries worldwide generally lack funds for climate change adaptation and mitigation projects (Locatelli et al., 2020; Pickering et al., 2015).

Traditional finance is about profit maximization, as it is concentrated on optimal risk and return combinations. No externalities are observed. In the 1970s, Friedman proposed corporate social responsibility, which has demonstrated its superiority in boosting corporate profits (Friedman, 2007). However, owing to the large upfront investment and long payback period, businesses and financial institutions tend to be skeptical about investing in pro-social or pro-environmental initiatives and projects (Jeucken, 2004). With the increasing public recognition of corporate externalities, value maximization gradually integrates considerations for various stakeholders, such as society and the environment; clean technology and other "green" opportunities with high financial viability attract more investor attention (Liu et al., 2021; Liu et al., 2022). With the introduction of the Equator Principles in 2002, the relationship between the environment and finance has become increasingly intertwined. As such, finance is progressing in a more pro-environmental manner.

Tamazian et al. (2009) stated that financial derivatives are essential for financing environmental protection projects. For example, the World Bank initiated the Global Environment Facility (GEF) to raise funds for environmental projects through partnerships between international institutions, social groups, and the private sector. Since then, financial instruments have been widely used in environmental protection and energy-transition projects. Governments worldwide have implemented legislation and fiscal and tax incentives to force or encourage the financial sector to adopt green management models (Stavins, 2003). Meanwhile, financial institutions have begun to integrate environmental and fiscal policies into economic development to attract private capital to participate in low-carbon businesses and projects (Aizawa and Yang, 2010; Dale and Newman, 2010). During the ongoing COVID-19 pandemic, governments worldwide have proposed and implemented "green recovery schemes" to stimulate economic recovery, underlining the importance of environmental protection and green energy transition for post-pandemic economic development (Chen et al., 2020; Wan et al., 2021). Firms, particularly those in the finance and environment

Table 1
Environmental finance keywords

Keywords	Start Year	No. of Articles
Sustainable finance	1992	226
Environmental finance	1972	39
Green finance	2010	82
Climate finance	2004	259
Energy finance	1971	127
Renewable finance	2013	3
Environmental Social Governance	2007	28
Environmental Social and Governance	2007	232
ESG	2007	180
Removed duplicates		284
Total		892

industry, play an essential role in accelerating the green recovery process. With innovative financial instruments and informed corporate environmental investments, economic recovery and carbon neutrality will enjoy a more balanced development pattern (Tian et al., 2020). Thus, environmental finance is becoming increasingly important.

The term "environmental finance" is frequently used in relevant research (White, 1996; Labatt and White, 2003). However, its definition is not universally established and is often confused with "green finance" and "sustainable finance". According to the Economic Commission for Europe (2017), "environmental finance" can be interpreted as "green finance", "green growth/economic finance", "eco-friendly finance", "sustainable finance", or "clean technology finance". Heinrichs et al. (2016) stated that "environmental finance" is generally referred to as "sustainable finance", while Ba et al. (2018) and some international research institutes (e.g., the IFC[3]) commonly refer to "environmental finance" as "green finance". The term initially referred to applying paradigms of environmental economics to finance and investment, and using financial derivatives to protect the environment (Sandor, 2017). However, the scope of the term has gradually broadened, as environmental financial instruments have evolved, the impact of environmental issues has deepened, and environmental regulations have strengthened. Accordingly, the concept of environmental finance will continue to evolve, with new aspects being added as time passes.

Current research on "environmental finance" covers a range of topics, including climate adaptation and mitigation (Allan et al., 2019; Linnenluecke et al., 2016; Sietz et al., 2011), energy price fluctuations (Apergis and Payne, 2010; Cadoret and Padovano, 2016; Jadidzadeh and Serletis, 2017), international cooperation (Morgan and Waskow, 2014; Ciplet et al., 2018), international policies (Nishimura, 2015; Hall et al., 2017), and capital markets (Henke, 2016; Tang and Zhang, 2020). However, existing studies on environmental finance are fragmented, and investigate relevant topics mainly from a financial perspective. Accordingly, a comprehensive interdisciplinary review is required to provide a holistic understanding of environmental finance-related topics. Therefore, this study fills this gap and uses bibliometric analysis to systematically review and discuss the current main research streams and emerging research trends in environmental finance. We also present a future outlook on environmental finance research by analyzing hot topics and trends, providing a reference for future research.

The remainder of this paper is organized as follows. Section 2 introduces the bibliometric analysis methodology. Section 3 investigates the most highly cited literature and key journals in the field of environmental finance. Section 4 identifies and systematically reviews the main research stream in environmental finance. Section 5 summarizes trending topics over the past five years using a keyword clustering timeline. Section 6 provides a future outlook on environmental finance research and concludes the paper.

[3] Source from: International Finance Corporation, https://www.cbd.int/financial/gcf/ifc-greentracking.pdf

2. Method

Using a bibliometric analysis technique, this study systematically reviews the existing research in the field of environmental finance. Bibliometric analysis uses quantitative methods to assess literature features, such as citations, co-citations, authors, publication journals, and keywords (Costa et al., 2017; Costa et al., 2019). Wang and Liu (2014) stated that bibliometric keyword mining can demonstrate the evolution of emerging research dynamics and frontier areas. Using *CiteSpace* software, this study conducts a bibliometric analysis of environmental finance-related papers published between January 1971 and June 2020 to identify influential research articles and their source journals.

Fig. 1 illustrates the literature screening process. As shown in the figure, we first identify the core literature in the field of environmental finance[4] and construct a citation diagram of relevant papers using *Connected Papers*[5]. We summarize the keywords from these papers that are highly relevant to environmental finance, and the preliminary result shows that: 1) commonly-used terms include "environmental finance", "green finance", and "sustainable finance"; 2) as the research field of environmental finance has become specialized, new terms such as "climate finance", "energy finance", "renewable finance", and "environmental, social, and governance (ESG)" have emerged.

To minimize selection bias, we further examine the ESG acronyms[6]. As "ESG" has different meanings in different fields, a two-step selection process is further conducted for this keyword. For the data selection process, we first select the categories most relevant to environmental finance, including environment, finance, economics, policy, and law, reaching a total of 328 articles (Appendix Table A2). Next, we manually remove papers with non-ESG acronyms[7], such as Eggshell Gland and Early Seeding Development, and obtain 180 ESG (Environmental, Social, and Governance)-related articles.

Table A1

Finally, this paper collects data from the Web of Science (WOS) core collection, with the document type of "article". We use these environmental finance-related keywords to search for relevant articles: environmental finance, sustainable finance, green finance, climate finance, energy finance, renewable finance, environmental social governance, environmental social and governance, and ESG. At this point, the initial sample includes 1,176 articles. We further clean the initial sample by removing repeated and irrelevant articles, reaching a final number of 892. Table 1 provides details of the keywords.

Fig. 2 illustrates the number of peer-reviewed journal articles on environmental finance published from 1971 to 2019[8]. From 1971 to 2006, the number of publications in the field of environmental finance was relatively low and stable; from 2007 to 2010, it demonstrated an initial increasing pattern, and since 2011, the growth rate of publications has increased dramatically and continued to rise year by year. In essence, the public has become increasingly concerned with environmental compensation and investment due to global warming, rising sea levels, and major environmental pollution accidents such as the Gulf of

[4] See Appendix Table A1 for the list of core literature.

[5] https://www.connectedpapers.com/

[6] We find a high degree of overlaps between the retrieved literature and the constructed database1 for other terms "sustainable investment", "green investment", etc.

[7] The removed non-ESG acronyms are: expert system generator\ eggshell gland\ electrosensillogram\ electroscaphognathitegram\ ecological state group \ eruca sativa gars\ esterified spent grain\ ecosystem services goods\ early seeding growth\ earth system governance\ eyestalk ganglia\ enhanced shale gas\ electrical strain gauge\ experimental study group\ ecological station of guaraquecaba\ ecological status groups\ evaluative space grid\ enhanced support group

[8] Given the sample ends at June 2020, to make the pattern more illustrative, we exclude the 2020 data from the diagram.

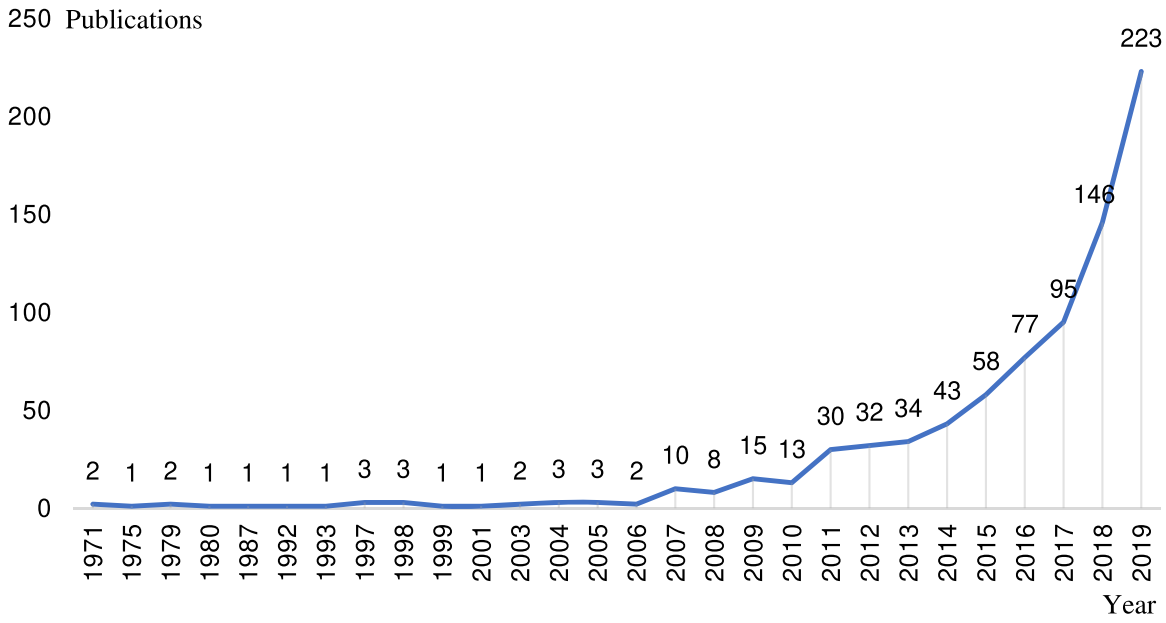

Fig. 2. Annual publications related to environmental finance

Table 2
Top 10 cited articles

Title	Author	Journal	Cited Count
1. Corporate social and environmental responsibility: A meta-analysis	Orlitzky et al. (2003)	Organizational Studies	59
2. The corporate social performance–financial performance link	Waddock & Graves (1997)	Strategic Management Journal	42
3. Corporate social responsibility and access to finance.	Cheng et al. (2014)	Strategic Management Journal	41
4. Strategic management: A stakeholder theory	Freeman (1984)	Journal of Management Studies	36
5. Does corporate social responsibility affect the cost of capital?	Ghoul et al. (2011)	Journal of Banking & Finance	36
6. Socially responsible investments: Institutional aspects, performance, and investor behavior	Renneboog et al. (2008)	Journal of Banking & Finance	33
7. The impact of corporate sustainability on organizational processes and performance	Eccles et al. (2014)	Management Science	28
8. Asset securitization, securitization recourse, and information uncertainty	Cheng et al. (2011)	Accounting Review	27
9. Misery loves companies: Rethinking social initiatives by business.	Margolis & Walsh (2003)	Administrative Science Quarterly	27
10. International evidence on ethical mutual fund performance and investment style	Bauer et al. (2005)	Journal of Banking & Finance	27

Table 3
Most cited source journals versus journals with most publications

Most Cited Source Journals		Journals with Most Publications	
Journal Title	***Cited Count***	***Journal Title***	***Publications***
Journal of Business Ethics	1414	Sustainability*	80
Energy Policy*	698	Climate Policy*	44
Journal of Cleaner Production*	562	Journal of Cleaner Production*	30
Journal of Finance	479	Business Strategy and The Environment*	24
Journal of Finance Economics	474	Energy Policy*	24
Strategic Management Journal	468	Journal of Business Ethics	23
Journal of Banking and Finance	428	Corporate Social Responsibility and Environmental Management*	17
Academy of Management Review	392	International Environmental Agreements-Politics Law and Economics*	14
Ecological Economics*	346	Ecological Economics*	11
Business Strategy and the Environment*	332	World Development	11
Total	5593	Total	278

Notes: * represents journals oriented to investigate environmental issues.

Mexico oil spill and Hungarian toxic wastewater spill. According to "*The global climate in 2011-2015*" (World Meteorological Organization, 2016), 2011 was a year of extreme weather events that resulted in significant economic losses. In 2012, Coumou and Rahmstorf published a paper linking extreme weather to economic losses, which has attracted more attention since then (Crecente et al., 2021). These increasing linkages between the environment and finance have contributed to the rapid increase in the number of publications in recent decades. The annual number of academic publications increased to 233 in 2019, indicating the growing importance of environmental finance.

3. Key articles and source journals

Through bibliometric analysis, this section investigates key articles and source peer-reviewed journals on environmental finance. Specifically, we analyze the references of the 892 articles and identify the most cited articles and journals that appear most in the references.

3.1. Highly Cited Articles

Table 2 lists the top 10 referenced articles. The most cited papers

Table 4
Main research streams of environmental finance

	Cluster Title	Keywords Covered		Obs.
#1	Corporate Social Responsibility	shareholder activism community management ethical investment stakeholder theory stock market firm performance social responsibility environmental performance ESG performance industry organization socially responsible environmental corporate governance sustainable development responsibility financial performance corporate governance social responsibility performance	economic performance sustainable finance firm valuation ESG rating environmental disclosure insurance corporate sustainability corporate fund return investor company investment CSR ESG determinant investment market sustainability	46
#2	Climate Negotiations	bureaucratic politics climate transparency adaptation climate negotiation Copenhagen accord UNFCC Paris agreement renewable energy climate finance mitigation development assistance climate change adaptation	foreign aid distribution inequality assistance game theory international investment newborn developing country CDM development accountability politics consumption conservation equity	35
#3	Natural Gas Price Volatility	economics volatility carbon market opportunity energy finance environment carbon challenge policy stock emission responsible investment	financialization dynamics evolution South Africa degradation valuation performativity allocation sequestration activism demand trade	26
#4	National Policy	reputation future system growth technology framework energy innovation economic growth	lesson diffusion greenhouse gas emission climate finance barrier clean development mechanism resource power	18
#5	Cost Comparison	management firm value immunization vaccination mutual fund performance social cost information	migration persistence financing Indonesia care nonfinancial disclosure ownership	16

focus on corporate social responsibility (CSR) and environmentally responsible investments. CSR papers provide stories about corporate sustainability, corporate responsibility, and environmental performance. Environmentally responsible investment research covers topics such as the balance between environmental investments and profits, externalities for stakeholders, and investor behavior. It should be noted that highly cited articles are mainly from business journals.

3.2. Source Journals

Table 3 displays the most referenced source journals (left) and journals that have published the most papers related to environmental finance (right). Among the most cited source journals, there are four journals oriented to solving environmental issues, including *Energy Policy, Journal of Cleaner Production, Ecological Economics*, and *Business Strategy and the Environment*, with a total cited frequency of 1998 (34.65% out of 5593). The remaining business journals account for approximately two-thirds of references. In contrast, among top 10 journals with most publications, the majority of them are sourced from environmental journals, with a proportion of 87.14%. Accordingly, although environmental journals have published more environmental finance-related papers, their impact (cited counts) is not as expected. Therefore, there is a need for more influential interdisciplinary research combining environmental topics with business and finance considerations.

4. Main research streams of environmental finance

We employ *CiteSpace* for keyword co-occurrence analysis of sample articles. This allows us to identify the main research topics through clustering analysis. The clustering results show that the top five clusters include more than 85% of all sample articles, while the remaining clusters only account for a small proportion. Therefore, we treat these five clusters as the main research streams of environmental finance. Based on the keywords of each cluster, we use latent semantic analysis (LSA) to name the title for each research stream. The results are provided in Table 4.

The LAS results show that the current five major research areas of environmental finance are: *Corporate Social Responsibility, Climate Negotiations, Natural Gas Price Volatility, National Policy*, and *Cost Comparison*. We systematically review each of the five environmental finance fields in the following subsections.

4.1. Corporate Social Responsibility (CSR)

In general, CSR is a form of corporate self-regulation that encourages a firm to make a positive impact on its stakeholders and the environment (Mackey et al., 2007). CSR encompasses a wide range of social, economic, and ecological dimensions as a result of various demands placed on a company by different stakeholders (Hernández et al., 2020; Barchiesi and Colladon, 2021). The complex dynamics of the social–economic–ecological system also create ambiguity in the definition (or classification) of CSR (Kanji and Chopra, 2010; Mishra and Schmidt, 2013; Roth et al., 2020). Researchers have contributed to the diversity of CSR definitions from various perspectives, most notably Carroll's (1979) "CSR pyramid" (Sheehy, 2015). In Carroll's article, the CSR framework includes four dimensions: economic responsibility, legal responsibility, ethical responsibility, and philanthropic responsibility (Carroll, 1991). Economic responsibility entails providing goods and services, which is the primary responsibility of firms (Crane et al., 2008). Legal responsibility and ethical responsibility shift the focus from a firm's economic interests to stakeholder interests, involving more social actors. Legal responsibility involves exercising rights and obligations in compliance with the law, both of which are fundamental precepts of an enterprise. In subsequent studies, researchers built on Carroll's work and developed the "beyond-compliance" theory. For example, in 2015,

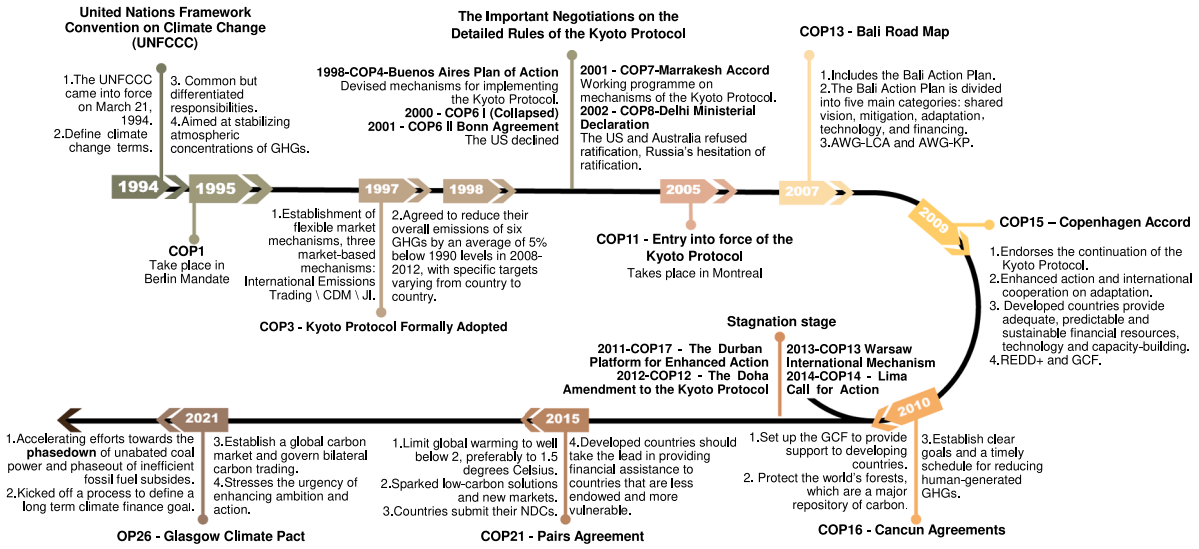

Fig. 3. Development of UNFCCC

Sheehy defined CSR as "international private business self-regulation" (Sheehy, 2015). Ethical responsibility represents a higher expectation of corporate performance in terms of adherence to business ethics and the consideration of stakeholders' interests (Ferrell et al., 2019). Finally, philanthropic responsibility refers to a company's voluntary pursuit of socially responsible practices by actively engaging in philanthropy that promotes human welfare (Kraus et al., 2020), which can reduce environmental externalities by encouraging corporate pro-environmental behavior and pushing CSR to a higher level (Wu et al., 2021).

An important way for companies to fulfil social responsibility is to invest in socially responsible projects. Socially responsible investment (SRI) is an investment strategy undertaken by companies to meet social responsibilities, while maintaining a balance between financial returns and economic benefits (Hirst, 2016). SRI can be a proxy variable for sustainability performance (Widyawati, 2020a). As ESG has gradually become the primary evaluation indicator for CSR performance (Widyawati, 2020b), SRI investors are beginning to use ESG metrics to assess their investment portfolios (Cellier et al., 2016).

ESG metrics reflect corporate ESG performance across three fundamental dimensions: environmental, social, and corporate governance. Currently, ESG rating organizations can be roughly divided into two categories: profit-making organizations and environmental organizations; in the SRI market, the ESG metrics issued by the former are commonly used (Wong et al., 2020). The world's largest ESG rating agencies include Morgan Stanley Capital International (MSCI), Sustainalytics, Financial Times Stock Exchange (FTSE), Thomson Reuters, and Bloomberg. The ESG metric systems used by these agencies share not only commonalities but also differences.

The commonalities are as follows: First, metric systems combine qualitative and quantitative analyses (Widyawati, 2020b). Second, they emphasize the dimensions of environmental sustainability and risk management (Galbreath, 2013). Third, many indicators are commonly used, despite different evaluation frameworks and calculation methods (Rahdari and Rostamy, 2015). Fourth, most rating agencies choose not to disclose their calculation methods because the details of the ESG evaluation process, such as specific indicators, are commercial secrets (Delmas and Blass, 2010). This also leads to a lack of transparency and comparability in ESG metrics (Chatterji et al., 2009; Escrig-Olmedo et al., 2014).

Meanwhile, metric systems have their distinctions. First, they have different evaluation objectives. The ESG metrics issued by MSCI, Sustainalytics, FTSE, and Thomson Reuters assess corporate ESG performance, whereas Bloomberg assesses the ESG disclosure level based on how much ESG data a company has released. Second, there are two types of ESG evaluation schemes. The first has a three-tier evaluation framework. The ESG rating (first-tier index) is calculated by the weighted average of the ratings in three ESG dimensions (second-tier index), namely the environment dimension, social dimension, and corporate governance dimension; then, the second-tier indexes are calculated using a different and specific index from each dimension (third-tier index), for example, human rights concern in the social dimension. Sustainalytics and Bloomberg ESG ratings use this evaluation framework. The other evaluation scheme divides each dimension into different subdimensions, forming a four-tier framework. This evaluation framework is mainly used by MSCI, FTSE, and Thomson Reuters.

4.2. *Climate Negotiations*

Facing growing climate challenges, countries worldwide have made joint efforts, such as establishing the United Nations Framework Convention on Climate Change (UNFCCC) and signing global cooperation treaties like the Kyoto Protocol, the Paris Agreement, and the Glasgow Climate Pact. However, there are large disparities between developed and developing countries in terms of climate justice, which has emerged as a core issue in climate negotiations (Morgan and Waskow, 2014). Climate justice is concerned with issues, such as carbon emissions accountability, climate fund allocation, and whether developed countries should provide assistance to developing countries. The challenge is to hold countries accountable for the adverse effects of climate change (Barrett, 2013). Although the UNFCCC has proposed the "Common but Differentiated Responsibilities" principle, the boundaries of these responsibilities remain unclear. Therefore, a multi-scale and interdisciplinary approach is needed to determine boundaries and uphold climate justice (Betsill and Bulkeley, 2006; Miranda et al., 2011).

Fig. 3 illustrates the timeline of climate negotiations' milestones, including the historical signing of the UNFCCC, Kyoto Protocol, and Paris Agreement, as well as other agreements primarily as a supplement and expansion of the three. The UNFCCC was signed in 1992 and came into force in 1994, setting a precedent for climate negotiations. It provided a framework for subsequent international negotiations and cooperation, leading to the signing of multiple global climate treaties.

However, the framework lacks specific emissions reduction targets or goals and has no legal binding force. To address the historical division of responsibilities in the UNFCCC framework and promote global climate change mitigation, the Kyoto Protocol sets quantitative limits on national greenhouse gas (GHG) emissions and allocates GHG emissions

as environmental resource property rights among countries. After a long period of negotiation and reconciliation among various actors, the Kyoto Protocol finally came into force in 2005. In 2007, participating governments agreed to adopt the "Bali Road Map" (including the "Bali Action Plan"), which continues the UNFCCC cooperation process (with the establishment of the AWG-LCA Task Force) and takes into account the commitments of the Kyoto Protocol (with the establishment of the AWG-KP), establishing a "dual-track path" for subsequent climate negotiations. However, despite multiple follow-up meetings, negotiations and global climate governance came to a halt because of participants' conflicting interests. It was not until 2015 that the Paris Agreement was reached, specifying long-term targets for GHG emissions beyond 2020 and requiring participants to submit "nationally determined contributions (NDCs)". The COP continued to be held every year. At the recent COP26, participants signed the "Glasgow Climate Pact", which, for the first time, included coal use reduction in the coal convention and reached an agreement on global carbon market trading rules. Simultaneously, the United States rejoined the Paris Agreement after withdrawing from it.

Although countries worldwide have competing interests in the global climate change negotiation, they have reached a consensus on the global governance of climate change by acknowledging that climate change has become an urgent issue. Most signed treaties stated the responsibilities of developed countries to assist developing countries in achieving global carbon neutrality (Heller and Shukla, 2003). This assistance includes financial aid, new technology development support, and technology transfer.

In terms of financial aid, it is estimated that high-income countries need EUR 5-10 billion each year to meet their carbon reduction commitments while providing assistance to countries with high ecological fragility (Gampfer et al., 2014). This massive funding deficit urges developing economies to raise their own funds for low-carbon initiatives (Bakker and Huizenga, 2010; Bowen, 2011; Winkler and Dubash, 2016). Consequently, climate finance has emerged as a solution to this conundrum. It has become an important instrument for countries worldwide to shoulder responsibility for climate change (Zadek, 2011). The main purpose of climate finance is to provide alternative financing tools for low-carbon actions and to eventually form a flexible carbon trading mechanism.

Currently, the most popular trading mechanism in the emerging carbon market is the Clean Development Mechanism (CDM) embedded in the UNFCCC. The Kyoto Protocol set a precedent for quantitatively restricting greenhouse gas emissions and distributing them as environmental property rights among countries. Such paid use of environmental capacity enabled the establishment of environmental property rights. Then, the Certified Emission Reduction (CER) credit (Sutter and Parreño, 2007; Subbarao and Lloyd, 2011) was created and became a unique climate currency (Pillay and Viñuales, 2016) in the financing and trading of the carbon market thereafter (Lecocq and Ambrosi, 2007).

4.3. Natural Gas Price Volatility

To mitigate carbon emissions and enhance economic feasibility, several major economies have chosen natural gas as their primary alternative energy resource (OPEC, 2015). As a major fossil fuel energy source, the price of natural gas will have a significant impact on the economy (Apergis and Payne, 2010; Bowden and Payne, 2009). Most relevant research has focused on the effects and influencing factors of natural gas price volatility.

Natural gas price volatility affects investment portfolios and risk management of natural gas producers and consumers. It also generates high economic costs. Natural gas has become the primary fuel in the United States (Bird et al., 2005). As natural gas energy becomes increasingly essential, the volatility of natural gas prices will affect energy prices and cause higher economic costs. High energy prices will further deepen poverty and inequality (Jakob and Steckel, 2014). Fortunately, there is certain substitutability between natural gas and crude oil, clean energy, renewable energy, and other new energy sources (Guo et al., 2021). For instance, power generation using renewable energy, such as photovoltaics, will reduce the power system's dependence on natural gas (Shahidehpour et al., 2005). Therefore, the price volatility of natural gas will have an impact on crude oil prices (Jadidzadeh and Serletis, 2017; Panagiotidis and Rutledge, 2007; Pindyck, 2004), clean energy prices (Avraam et al., 2020; Weijermars et al., 2011), share prices of renewable energy companies (Bird et al., 2005; Pereira et al., 2020) and electricity prices (Shahidehpour et al., 2005). Substituting natural gas power generation with renewable power generation (Bolinger et al., 2006) will offset some of the adverse effects of natural gas price volatility (Bird et al., 2005).

Factors influencing natural gas price volatility include an increase in clean energy (Cadoret and Padovano, 2016; Kumar et al., 2017; Wan et al., 2021), crude oil price fluctuations (Krichene, 2002; Villar and Joutz, 2006; Regnard and Zakoian, 2011), weather changes (Considine, 2000; Yang et al., 2020), strengthened market supervision (MacAvoy, 2008; Apergis and Ozturk, 2015), and global commitments to low-carbon emissions and sustainable development (Janssen et al., 2006; Yang, 2018). Crude oil and natural gas prices, for example, are highly correlated (Asche and Misund, 2016; Geman, 2009), and weather changes induce demand shifts and price swings for natural gas (Elkhafif, 1996; Mu, 2007). Meanwhile, substituting natural gas with renewable energy will overcome the limitations of the current energy consumption structure and accelerate the progress of sustainable development (Apergis and Payne, 2010). However, energy poverty and the high upfront cost of renewable energy remain the most significant impediments to energy transition (Yu et al., 2022).

4.4. National Policy

The United Nations has assigned decarbonization responsibility to governments (Nishimura, 2015) because the private sector lacks the motivation to perform socially responsible activities (Ho and Park, 2019). To combat climate change, the United Nations has established a practical policy framework known as Climate Policy Integration (CPI) (Rietig and Perkins, 2018; Ghazouani et al., 2021). Major economies, such as the European Union, the United States, and China, have implemented corresponding policies to guide all sectors towards low-carbon transition and encourage financial institutions to utilize financial instruments to mitigate environmental pollution. Common strategies undertaken by governments involve environmental legislation and regulation, carbon reduction policies, and incentives for the financial sector to participate in green projects with innovative financial instruments.

Countries worldwide have established multiple legislations and regulations to provide a legal basis for monitoring emission reduction efforts. For example, the United States has enacted "*Comprehensive Environmental Response, Compensation, and Liability Act*" (Bearden, 2012), "*Energy Policy Act of 2005*", and "*American Clean Energy and Security Act*" (Gold et al., 2009; Montgomery et al., 2009). The United Kingdom has implemented the "*Climate Change Act*" (Lockwood, 2013). The European Union has enacted the "*European Climate Law*". China has also issued the "*Energy Conservation Law*" and "*Renewable Energy Law*". Legislation and regulation have substantially reduced carbon emissions and regulated energy consumption in major economies, such as the United States, the United Kingdom, the European Union, and China.

Moreover, emission reduction policies have been implemented in many countries. The most widely adopted carbon emission policy is Carbon Pricing (Hepburn, 2006; World Bank, 2019a,b). There are two types of carbon pricing mechanisms: carbon emissions trading, which controls the quantity of carbon emissions, and carbon taxation, which regulates emission prices (Burney, 2010; Haites, 2018). In carbon emission trading mechanism, the government issues emission permits up to the preset limit of carbon emissions and then leaves the market to

determine the price (Stavins, 2003). The carbon taxation mechanism works in the reverse way: the government sets the price of carbon emissions based on tax rates, and companies decide the limit of their emissions accordingly (Hepburn, 2006; Shahzad et al., 2021). Carbon emissions have a typical economic externality that can be internalized through carbon pricing (Kempa and Moslener, 2017; Bashir et al., 2021). Carbon pricing has been implemented in many countries and has generated positive outcomes (Nachmany et al., 2015; Pollitt, 2016; World Bank, 2018; Ghazouani et al., 2021).

In addition, governments worldwide have provided incentives to encourage private capital to participate in low-carbon investments. Many policy-oriented financial institutions have adopted a vast range of strategies, such as loss sharing and credit sharing, to raise funds from individuals to invest in large ventures. For instance, from 2009 to 2014, the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) invested approximately US$95 million in energy transition projects, 22 of which subsequently received a cumulative private investment of more than US$625 million. This shows that governments can attract private investment by supporting green projects from the outset, giving full play to the leveraging effect of policy-based environmental finance.

Energy and climate policies can generate reasonable returns through efficient market mechanisms (Hall et al., 2017; Huang et al., 2021). Unfortunately, in the past, carbon emission policies were greatly hampered by inefficient financing approaches, hindering the low-carbon transition (Sullivan et al., 2013). In addition to measures such as legislation and regulation, carbon pricing, and investment incentives, researchers and policymakers should also consider efficient financial instruments, such as public-private partnerships (PPPs) and carbon emission transfers. Thus far, carbon emission transfer has seldom been incorporated into policies (Springmann, 2014).

4.5. Cost Comparison

Researchers have widely recognized the impact of CSR practices on corporate financial performance. CSR practices affect corporate costs, revenues, and firm value. Corporate costs are highly related to resource allocation, efficiency, and sustainability. This section compares corporate costs under various CSR expenditures.

Research on CSR costs primarily focuses on costs of capital and debt. Previous studies have shown that CSR disclosures reduce the cost of capital by mitigating information asymmetry among stakeholders (Branco and Rodrigues, 2006). Moreover, voluntary CSR practices attract socially conscious investors (Escrig-Olmedo et al., 2017) and add corporate bond premium (Richardson and Welker, 2001). This produces a positive valuation effect (Chauhan and Kumar, 2019; Lueg et al., 2019), further reducing a company's cost of capital (Atan et al., 2018).

In terms of cost of debt, environmental regulations in various countries have increased cost of compliance, causing great uncertainty with respect to corporate solvency (Andrade et al., 2014). Erragragui (2018) noted that, although environmental issues increase the cost of debt for businesses, superior corporate environmental performance and corporate governance would eventually reduce the cost. This is because when companies take the initiative to undertake social responsibilities, such as pollution control, they minimize their potential regulatory risks, thereby lowering their cost of debt (Nikolaev and Van Lent, 2005; Weber, 2014; Wu et al., 2019; Sahut et al., 2021).

Existing research has not reached a consensus on the impact of corporate socially responsible investment on company performance. Some scholars believe that the costs of CSR investment outweigh its gains and are not conducive to corporate growth (Marsat and Williams, 2014). Nevertheless, others suggest that voluntary CSR practices reduce government supervision of a firm's operations and lower its cost of compliance, thereby contributing to its long-term sustainability (Dhaliwal et al., 2011).

Generally, CSR practices may have a positive effect on reducing corporate debt. Companies have made great efforts to improve their CSR performance in order to gain a competitive edge in the global market (Škare and Golja, 2012; Ferrero-Ferrero et al., 2016). Moreover, CSR practices can mitigate potential systemic risks (Lueg et al., 2019), leading to a win-win situation for companies, investors, and society as a whole (Sudha, 2015).

5. Emerging research areas of environmental finance

Through the LSA of articles published in the recent five years (from 2016 to 2020), we illustrate a timeline for the progress of emerging research areas in environmental finance. Fig. A1 in the Appendix shows the progress of each emerging research theme. The top five emerging themes of environmental finance are: *Climate Finance, Sustainable Finance, Firm Value, Risk* (Climate Risk and Regulation Risk), and *Debt* (Green Bonds). The following five subsections review each of the five emerging areas.

5.1. Climate Finance

In recent years, climate finance has been a leading topic in the field of environmental finance. The UNFCCC defines it as "*local, national, or transnational financing drawn from public, private, and alternative sources of financing that seek to support mitigation and adaptation actions that will address climate change*." In a narrow sense, it refers to the financial mechanisms through which developed countries provide relief funds to developing countries within the global cooperation framework. Broadly, it extends to mitigation and adaptation actions to address climate change issues.

In 2019, the World Bank reported that a low-carbon transition would require a large amount of funding (World Bank, 2019a). By 2025, developing and middle-income countries will need approximately US $90 trillion to build new environmental infrastructure to combat climate change. The funding requirement for climate mitigation and adaptation activities amounts to approximately US$3-100 billion per year from 2010 to 2050 (Peña-López, 2009). The scale of funding deficit varies across countries because different countries have different capabilities and obligations under the climate change response framework, have made different climate commitments in different periods, and are in different economic development stages. The "*World Development Report 2010*" revealed that the finance required for a low-carbon transition in developing countries amounts to US$14-17.5 billion per year. Although developed countries promised to offer US$100 billion in aid each year at the *Copenhagen Conference*, there are still large funding deficits (Parry, 2010).

To fix this deficit, policymakers worldwide are experimenting with various financing models (Cui et al., 2021). The global climate financing model has evolved from government-or public-funded to privately funded. Government or public funding is the basic financing method for infrastructure investments (Engel et al., 2013). Multilateral climate funds, such as the Global Environment Facility (GEF), Adaptation Fund (AF), Climate Investment Funds (CIFs), and Green Climate Fund (GCF), are major public financing instruments. The sources of these funds include donations from countries, debt financing, equity financing, and proceeds from projects. For example, GEF acquires funds primarily through donations (GEF, 2021), and AF is largely supported by the Clean Development Mechanism (CDM) project.

However, the public budget alone is not sufficient to support climate change investment (Gouldson et al., 2015). To compensate for this deficit (Pauw and Pegels, 2013), governments are encouraging private investors to participate in climate investment (Schmidt, 2014). There are two types of private investors: institutional and individual investors. Institutional investors include pension funds, insurance companies, commercial banks, and wealth funds (Colenbrander et al., 2018). Private funding institutions generally respond more quickly than public funds. However, they have several drawbacks, such as a lack of legitimacy,

consistency, and sense of responsibility. The solution to these problems is to partner public funding with private funding. The joint regulatory system for PPPs will maximize the interests of investors and stakeholders (Ho and Park, 2019), and the combined governance structure will improve the financing efficiency of the public sector (Xiong et al., 2020). Emerging crowdfunding platforms provide excellent investment instruments for individual investors. Different types of crowdfunding methods include donation-based, reward-based, loan-based, and equity-based crowdfunding (Kirby and Worner, 2014; World Bank, 2013). This funding approach has already been applied in renewable energy investments, such as the World Wildlife Fund-China Giant Panda Program and the Tanzania solar on-demand project. So far, clean energy and sustainability initiatives have raised more than GBP 320 million worldwide through crowdfunding, giving rise to a range of green project fundraising platforms, such as Kiva and Global Giving.

5.2. Sustainable Finance

The European Commission defines sustainable finance as "*the process of taking ESG considerations into account when making investment decisions in the financial sector, leading to more long-term investments in sustainable economic activities and projects*." To achieve sustainable development, energy transition has become the focal point of sustainable finance (Gonzalez, 2021). Sustainable finance entails a new market mechanism (NMM) and sustainable development. NMM is an umbrella term for carbon emission trading systems, whose purpose is to help the international community accomplish a low-carbon transition and improve social and economic sustainability by maintaining ecosystem resilience (Jakob et al., 2016).

The NMM is part of emissions trading in carbon pricing. The mechanism assigns a predetermined number of emissions permits to emitters. Permits become valuable because of their scarcity (Stavins, 2003; Garnaut, 2008). In this way, a market with emission permits as a trading object is formed. This emission trading mechanism helps enhance the efficiency of emission reduction (Newell and Bulkeley, 2017; Ulucak et al., 2019).

The carbon market operation model can be categorized into two types: Emission Trading Schemes (ETS) and Offset Schemes (MacKenzie, 2009). ETS balance carbon emissions in different regions and increase carbon emission costs by setting emission caps and permits through emission permit trading (World Bank, 2007; MacKenzie, 2009; Cui et al., 2021). Offset Schemes are used for carbon credit trading (MacKenzie, 2009; Ockwell et al., 2008). The United Nations' CDM is the world's largest offset scheme, which allows countries/regions that have exceeded their emission quotas to purchase certified emission reductions (CERs) to offset their emissions (Lecocq and Ambrosi, 2007; Knorr and Eisenkopf, 2020), thereby contributing to carbon neutrality.

However, there are still many problems in carbon markets. First, the initial allocation of carbon emission permits and determination of their prices are not well regulated (Goulder and Schein, 2013). In 2005, the EU emission trading system allocated a large share of emissions permits in the initial phase of the trading process. The large initial share of emissions permits left companies with no need to purchase additional permits in the market, which substantially delayed the rollout of emission trading schemes (ICPA, 2017). Second, discrepancies in carbon prices exist globally. Such discrepancies have contributed to the carbon leakage caused by carbon emissions transfers between nations during international trade (Flannery et al., 2006). As emission restrictions in some countries increase corporate costs, companies tend to transfer their production lines from emission-restricted countries to non-restricted ones. While restricted countries may meet emission reduction targets, the reduced emissions will be offset by the emissions transferred to unrestricted countries, resulting in an overall increase in global carbon emissions. Third, there is a lack of regulation for the emission trading system. Inadequate supervision will cause polluters to emit more than their allowances; therefore, regulators need to measure, report, and verify actual emissions (Ellerman and Buchner, 2007). Moreover, companies may obtain carbon emission permits through unethical practices owing to the scarcity of permits, leading to more serious corruption.

There are two types of carbon market supervisions: distributed and centralized supervision (Kahana et al., 2008). Blockchain is a typical distributed supervision method characterized by decentralization and immutability. It demonstrates excellent potential for the regulation of carbon markets. Related research focuses on establishing a new carbon market using blockchain technologies, such as Networked Carbon, Industry 4.0, Technolibertarian, and Voluntary Offset (Macinante, 2016; Aste et al., 2017; Leonhard, 2017a,b; Khaqqi et al., 2018; Chinchilla, 2020). Owing to the large funding requirement, it is difficult to create a new market in a short period of time (Hartmann and Thomas, 2020). A more realistic option is to apply blockchain technology to the existing carbon market. Unfortunately, only a few studies have been conducted on this topic.

5.3. Firm Value

Research on firm value is primarily concerned with the impact of corporate socially responsible investments and non-financial information disclosures on firm value. These impacts include capital cost reduction, effective financial risk control, and operating cash flow growth.

CSR investment has a significant effect on firm value. On the one hand, disclosing CSR investment information increases corporate reputation, credibility, and brand value (Crifo et al., 2015), attracts investors (Cheng et al., 2015) and thereby boosts firm value. On the other hand, CSR practices generate additional returns for businesses (Ambec et al., 2013); therefore, appropriate ESG performance improves corporate financial performance (Zhao et al., 2018). Friede et al. (2015) analyzed 2,000 articles on "the relationship between ESG and Corporate Financial Performance (CFP)" and concluded that ESG and CFP have a positive relationship. Therefore, it makes sense that improving ESG rating has become an emerging priority while designing a corporate competitive strategy (Gifford, 2010; Galbreath, 2013; Segarra-Oña et al., 2016).

In recent years, non-financial disclosures have evolved from a single CSR disclosure to a more comprehensive ESG disclosure. With ESG investments being gradually embraced by mainstream investors, ESG disclosures have now become more voluntary than required. Although ESG disclosure has been mandated in many countries and regions (Friede et al., 2015), the international ESG disclosure system still largely relies on voluntary disclosure. Nonetheless, with increasing public attention and expectations for ESG disclosures, more companies are adopting sustainable strategies and voluntarily disclosing ESG information (Freeman and McVea, 2001; Brockett and Rezaee, 2012), providing hope for developing ESG evaluation schemes.

In general, a considerable body of literature has focused on the correlation between non-financial information disclosures and CSR in developed countries (Miralles-Quirós et al., 2019), while research on developing countries remains scarce (Bing and Li, 2019). Therefore, researchers and corporate decision-makers should pay more attention to the impact of non-financial information disclosures and CSR on firm value in developing countries.

5.4. Climate Risk

Another emerging topic in environmental finance is the study of climate risk (Kreft et al., 2013; Zscheischler et al., 2018; Eckstein et al., 2019; Farbotko, 2020). Zscheischler et al. (2018) extended the IPCC

framework of climate risk by arguing that climate-related risk is driven by both climatic and non-climatic drivers. Krueger et al. (2020) and Seltzer et al. (2020) stated that climate risk affects the market through three main pathways: physical risk caused by climate change, regulatory risk caused by regulation change, and technological risk caused by disruptive innovation in environmental technologies.

Climate (change) risk refers to the probability of economic losses incurred due to extreme weather events, including heatwaves, droughts, and tornadoes, as well as emergencies, such as fires, floods, and tsunamis. Natural disasters caused by climate change can result in significant damage to the property of residents and businesses. In the case of the insurance industry, massive property losses increase the pressure on insurance firms to pay claims (Campiglio et al., 2018). Moreover, the losses of residential and corporate assets increase the proportion of liabilities, resulting in an increased risk of default and various accumulated financial risks, all of which have a significant impact on the stability of the financial system . Therefore, it is important to develop a climate risk indicator to monitor and manage possible climate change risks. Germany published the Climate Risk Index in 2008, 2014, and 2019, but there is a lack of similar studies and reports from other countries. Sautner et al. (2020) provided new insights for calculating firm-level climate risk indices from 34 countries using transcripts of the corporate earnings conference call, highlighting the importance of corporate climate risk on corporate sustainability

Regulatory risk refers to the impact of environmental regulation changes on a firm's production and operations (Singh et al., 1986; Sharfman and Fernando, 2008; Seltzer et al., 2020). The impact of environmental regulation depends on the manner, scope, and intensity of the regulation (Song et al., 2020a; Huang et al., 2021). For example, government regulations that require firms to engage in environmentally responsible behavior can significantly increase their cost of compliance (White, 1996; Zhang et al., 2020b), whereas environmental subsidies and incentives, such as government-supported renewable energy policies, can help firms grow (Zhang et al., 2021a; Tian et al., 2022). Policy uncertainty can also affect investors' willingness to invest in certain sectors (Barradale, 2010; Polzin et al., 2015). To maintain financial market stability, such uncertainty should be managed through appropriate regulations. Inadequate regulations may result in disclosure risk for firms that do not disclose sufficient non-financial information (Hess, 2019). However, excessive intervention may bring price risk, which refers to the uncertainty of changes in the prices of related products.

Technological risk primarily refers to transitional risk (Campiglio et al., 2018) caused by disruptive innovations in environmental technologies (Geels et al., 2017), such as the structural risk arising from energy mix replacement (Semieniuk et al., 2021). During energy transition, when the original energy structure is disrupted and the traditional energy supply chain contracts, a certain temporal and spatial discontinuity is triggered because the new energy system is not yet mature and the business succession capacity is limited, resulting in transitional issues such as structural unemployment (Almutairi et al., 2018; Mu et al., 2018) and regional energy poverty (González-Eguino, 2015; Carley and Konisky, 2020; Zhai et al., 2022). During this process, transitional risks often converge with multiple risks such as financial and regulatory risks.

5.5. Green Bonds

Green bonds are issued to fund environmental projects and help achieve the sustainable development goals (SDG 7 and 13[9]) proposed by the United Nations. The International Capital Market Association (2018) released the "Green Bond Principles", which explicitly define projects eligible for funding through green bonds. It specifies that green projects include, but are not limited to, renewable energy initiatives, pollution prevention, sustainable environmental management, biodiversity protection, and clean transportation. Since the launch of green bonds in 2007, the global green bond market has expanded exponentially (Tolliver et al., 2020), setting off a "Green Bond Boom" worldwide (MorganStanley, 2017).

However, research on green bonds lags behind that on market development (Flammer, 2021). Studies on green bonds concentrate primarily on their floating interest rates, liquidity, and premiums. Zhang et al. (2020) concluded that the floating interest rate of green bonds is linked to the carbon price; the higher the carbon price, the higher the coupon payment. In addition, investors in the stock market respond positively to corporate environmental practices (Flammer, 2013; Krüger, 2015) because of the high premium of green bonds (Tang and Zhang, 2020), although they often cannot verify corporate environmental actions due to information asymmetry (Lyon and Maxwell, 2011; Lyon and Montgomery, 2015; Karpf and Mandel, 2017). Green bonds enable companies to acquire funds at a lower cost of capital (Flammer, 2021). Accordingly, green bonds have become an increasingly important research topic in the field of environmental finance instruments.

5.6. Summary

With the increasing frequency of extreme weather events, there is now a global consensus to address climate change issues and promote low-carbon transition (Zhao et al. 2022). As shown in Fig. A1, the hot topics of emerging research related to environmental finance include a wide range of areas, such as financing (climate finance and sustainable finance), the development of market mechanisms (firm value and green bonds), and climate-related risks (climate risk). These topics are both distinct and interconnected.

In the early stages of industrialization, rapid capital growth is fueled by huge energy consumption, resulting in a slew of climate and environmental risks. In recent years, global climate change has triggered an increase in various types of catastrophic events and has had a serious impact on socioeconomic development. Countries worldwide have reached a consensus on addressing climate change; however, owing to the externalities of climate change and the complexity of climate governance, there is a significant funding gap for climate change mitigation and low-carbon transition. To close this financing gap, governments, financial institutions, and international organizations are actively exploring new market mechanisms and innovative financial instruments. Notably, firms and non-financial institutions have also emerged as key players in climate governance alongside financial institutions, such as commercial banks and fund companies.

6. Discussion and conclusions

6.1. Discussion

Climate issues such as global warming pose a severe threat to human health and well-being (United Nations, 1992). To combat climate change, countries are working together to reduce carbon emissions and achieve carbon neutrality. Governments are transitioning toward renewable energy solutions to meet their commitments to energy conservation and emission reduction. Renewable energy resources, such as solar and wind, have become more popular in recent years; however, the high cost of renewable energy infrastructure has impeded the speed of clean energy development, especially in developing countries. Therefore, it has become imperative for the global community to introduce innovative and practical financing methods. Researchers have already turned their attention to the financing method of environmental projects, which has largely shifted from government/publicly funded to

[9] SDG 7 Affordable and Clean Energy: ensure access to affordable, reliable, sustainable and modern energy for all; SDG 13 Climate Action: take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy.

privately funded, representing a breakthrough for environmental financing. With the growing inflow of private capital in environmental projects, environmental finance research has extended to CSR investment such as ESG metric development. The key areas of environmental finance are further discussed below.

6.1.1. Financial Instrument Innovation

Innovative financial tools are a significant driving force for environmental finance. Environmental governance combined with green finance has greatly encouraged environmental property rights trade, attracting significant research interest. Green finance involves climate funding mechanisms, such as carbon taxation, carbon markets, and other financial instruments, like green bonds and greed funds. However, there is a lack of research on the following aspects:

First, it is imperative to introduce a framework for quantifying the costs of climate change. Problems have emerged in climate governance owing to the lack of a framework, especially the inconsistency between carbon emissions and emission-driven losses, as well as the issue of intergenerational equity in global climate policy. Regarding the inconsistency between carbon emissions and emission-driven losses, countries with high ecological fragility often suffer more from climate change problems, even though they are not primary carbon emitters. Therefore, a comprehensive framework for quantifying climate-change-driven losses is required. The intergenerational equity concern in global climate policy has become urgent because of the dynamic state of climate change. As climate change damages might endure for decades, it is essential to develop an evaluation model for climate change losses and their discount rates across years, thereby clarifying the responsibilities of each country.

Second, evaluation models related to carbon markets require further improvements. Carbon pricing has increased the corporate costs of carbon emissions. The costs vary among countries owing to various carbon tax rates. Therefore, companies may move their production lines to countries with lower emission costs owing to laxer emission policies, leading to carbon emission leakage to these countries. Currently, most scholars use the multi-regional input-output model to estimate the carbon emissions being transferred (Xiao et al., 2022), despite limitations in model assumption, collection, optimization, and data availability. Moreover, estimation models related to carbon offset should be improved. Carbon offset refers to the maintenance of carbon neutrality via green policies, such as afforestation and renewable energy transition. Existing quantification methods for carbon emissions include carbon footprint calculation and direct estimation of carbon emissions. However, these methods neglect the volume of carbon dioxide released from renewable energy production. Therefore, a national carbon emission calculation model should integrate individual carbon footprints, industrial carbon emissions, and carbon emissions from renewable energy production. Furthermore, as carbon markets are still at an early stage of development, computational models for carbon tax rates require further exploration.

Third, advanced theories and methods are required for the development of green financial instruments. Traditional pricing models and investment strategies have proven to be insufficient for pricing and investment in modern environmental finance. For example, the price of green bonds has been clearly underestimated through traditional pricing models owing to environmental externalities, government subsidies, and investor irrationality. The pricing model for green bonds should be designed to account for their lack of market orientation, which stems from the mismatch between the short-term nature of investment and financing, and the long-term return cycle of green projects. Large-scale green projects rely heavily on government financial support, undermining the inherent capital allocation capacity of the capital market.

Fourth, governments should intervene in green capital markets only when necessary. Appropriate protection and incentive policies positively impact environmental financial markets at an early stage. However, excessive government intervention stifles market vibrancy, causes social resource misallocation, and induces rent-seeking behaviors, leading to an unhealthy environmental financial market. For example, government over-intervention increases the premium of green bonds and increases the cost of debt. Accordingly, lower-than-expected returns deter potential investors. The increased premium on green bonds inhibits long-term green investments, resulting in a decline in green project output. Therefore, in the event of market segmentation, the government should exercise restraint when implementing policies to guide the development of the environmental financial market.

6.1.2. Energy Transition

Energy transition is key to carbon emission reduction, climate governance, and climate change mitigation. However, this approach presents several challenges.

First, geopolitical risk has brought uncertainty to energy transition. A balance between energy security and climate change during the global energy transition is required. Previous studies have shown that energy transition will reshape the global energy structure (Scholten et al., 2020). However, escalating geopolitics has intensified the uncertainty of energy transition. Overall, geopolitics has turned the energy transition into a technological race; countries that first completed the energy transition will lead the economy after the green industrial revolution.

Moreover, the competitiveness of clean energy sources remains insufficient. Currently, energy transition relies heavily on government policy support. The expansion of new energy service capacity is key to promoting energy transition. However, most renewable energy sources have intermittency and immediacy issues in terms of power generation (Steele et al., 2021). For example, wind-generated electricity cannot be stored in large quantities, and must be used immediately. In addition, wind power plants are typically located in sparsely populated suburban areas, resulting in increased expenses for electricity transmission. Usage immediacy and high transmission costs have led to the stubbornly high cost of renewable energy services. Governments worldwide have put in place a variety of policies to encourage the use of clean energy; however, policy-driven energy transition may be jeopardized if policy changes. Therefore, overcoming the high cost of new energy services is the primary driving force behind the energy transition, and it is also a goal that the United Nations is currently pursuing (SDG7: Affordable and Clean Energy).

Furthermore, energy transition has caused ecological and environmental losses. In the context of global climate governance, attention needs to be paid to the environmental issues brought on by energy transition. Although renewable energy helps reduce carbon dioxide, its production process causes environmental problems, such as pollution and ecological damage. For example, studies have shown that if a natural basin is damaged by hydropower construction, the morphology of the upstream and downstream systems and the characteristics of the estuary changes accordingly (Clare, 1992). As environmental and ecological systems are closely interconnected, ecological problems accumulate and expand, eventually causing substantial ecological losses. Nuclear power is another example, as it has several drawbacks, most notably, radiation contamination. After the 2011 Fukushima nuclear leak, the Japanese government faced many challenges, including large-scale evacuation of nearby populations, food safety concerns, and water contamination (Kharecha and Sato, 2019). Frequent nuclear leaks have raised global concerns about nuclear safety, prompting countries such as Germany, Switzerland, and South Korea to phase out nuclear power gradually. Therefore, countries should consider the environmental losses of clean energy production and be environmentally conscious when developing clean energy infrastructure.

6.1.3. Environment, Social, and Governance (ESG)

ESG metrics are commonly used to assess CSR practices. Although ESG metrics are growing in popularity worldwide, the following problems remain:

First, the definition of ESG metrics remains unclear. The boundaries of ESG matters are not clearly defined, which leads to inconsistent positions of CSR investment and varying qualities of CSR reports.

Second, standards for ESG indicator systems are lacking. Widely used ESG indicator systems worldwide are issued by different agencies. These systems have various weighting methods for the ESG components and different interpretations for each ESG dimension. For example, Bloomberg assesses non-discrimination-related problems from various perspectives with details of the social dimension, whereas Thomson Reuters assesses these issues from a relatively broad perspective.

Third, the ESG rating scheme deviates from its intended purpose in practice. Currently, ESG reports are mainly concerned with exposing potential environmental consequences posed by corporate operations, while the purpose of ESG ratings is to encourage companies to actively take on environmental responsibility.

6.2. Conclusions

Using data from the Web of Science database, this study employed bibliometric analysis to systematically review the current mainstream and emerging research areas of environmental finance. Environmental finance is an interdisciplinary subject combining environmental science, finance, and management. Our results show that the number of publications in this field has grown substantially since 2010. Through keyword cluster analysis, we identified five main research areas of environmental finance: *corporate social responsibility, climate negotiations, natural gas price volatility, national policy*, and *cost comparison*. We also outline emerging research topics in environmental finance, including *climate finance, sustainable finance, firm value, climate risk, regulation risk*, and *green bonds*.

In contrast to traditional finance, environmental finance internalizes externalities by considering climate change mitigation and environmental governance. Environmental investment and financing have shifted from focusing solely on the economy to integrating the economy and the environment. Currently, environmental finance is widely practiced globally. It is mainly designed to address the United Nations' sustainable development goals—SDG 7 of Affordable and Clean Energy and SDG 13 regarding Climate Action by leveraging financing tools to enhance public access to affordable, reliable, sustainable, and modern energy, as well as providing financial support to promote renewable energy and combat climate change and its impacts. The main actors in environmental finance include international organizations, governments, environmental organizations, and institutional investors. Research topics that can be further explored in environmental finance include financial instrument innovation, energy transition, and ESG. Financial instrument innovation covers topics, such as climate change compensation accounting, carbon emissions estimation model development (e.g., carbon tax rate setting, micro carbon emissions accounting, green consumption ecological system, and carbon emissions of renewable energy), environmental finance and economic theories (e.g., the integration of natural and social sciences with economics, such as the economic theory of emissions reduction and green bond theory), and improvement of green market mechanisms. Energy transition covers topics, such as the price of new energy technologies, ecological losses and economic risks from energy transition, energy value chain, how to overcome the high cost of clean and renewable energy services, how to smoothly complete energy transition, and whether energy transition will cause structural and systemic imbalances. ESG encompasses topics, such as the definition of ESG and the development of the standardized ESG rating system. These topics interact and co-evolve with each other, generating a research agenda for environmental finance.

CRediT authorship contribution statement

Hu Tao: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft. **Shan Zhuang:** Data curation, Investigation, Writing – original draft. **Rui Xue:** Conceptualization, Formal analysis, Methodology, Validation, Writing – review & editing. **Wei Cao:** Data curation, Validation, Writing – review & editing. **Jinfang Tian:** Resources, Writing – review & editing. **Yuli Shan:** Conceptualization, Methodology, Writing – review & editing.

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Appendix

Table A1
Environmental finance related articles

Authors	Title	Citations
(Labatt and White, 2002)	Environmental finance: A guide to environmental risk assessment and financial products	88
White (1996)	Environmental finance: Value and risk in an age of ecology	32
Linnenluecke et al. (2016)	Environmental finance: A research agenda for interdisciplinary finance research	49
(Wang and Zhi, 2016)	The role of green finance in environmental protection: Two aspects of market mechanism and policies	122
(Hoti et al., 2007)	Measuring risk in environmental finance	30
Gray (2002)	Of messiness, systems and sustainability: Towards a more social and environmental finance and accounting	120
Sachs et al. (2019)	Importance of green finance for achieving sustainable development goals and energy security	37
(Dikau and Volz, 2021)	Central bank mandates, sustainability objectives and the promotion of green finance	55
(Fatemi and Fooladi, 2013)	Sustainable finance: A new paradigm	86
Lindenberg (2014)	Definition of green finance	35
Jeucken (2004)	Sustainable finance and banking: The financial sector and the future of the planet	216
Soppe (2004)	Sustainable corporate finance	75

Table A2
Environmental finance related categories

Categories	Count
Environmental Studies	103
Business	98
Management	89
Environmental Sciences	76
Green Sustainable Science Technology	74
Business Finance	67
Environmental Sciences	38
Engineering Environmental	16
Economics	28
Ethics	21
Law	11
Operations Research Management Science	9
Energy Fuels	7
Engineering Civil	7
International Relations	6
Development Studies	5
Political Science	4
Public Environmental Occupational Health	4
Sociology	4
Total	328

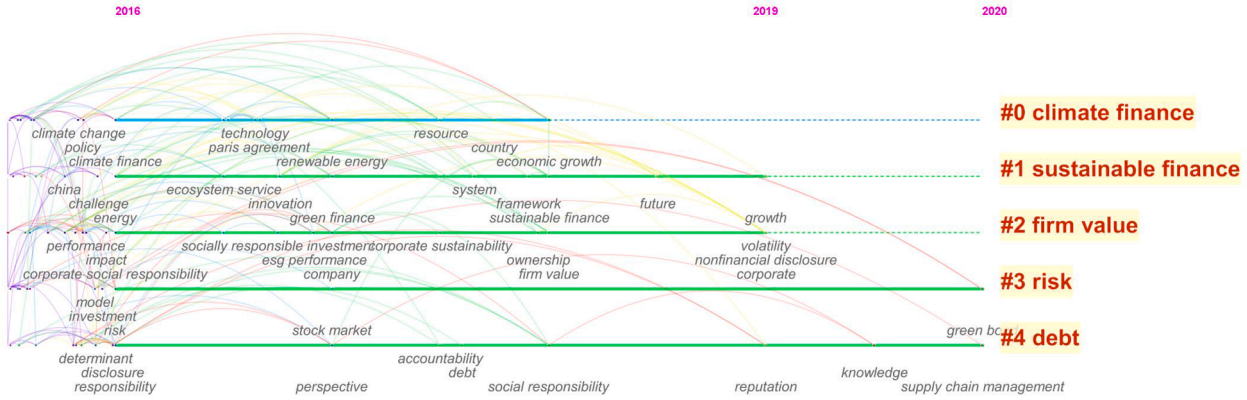

Fig. A1. Timeline of main research areas of environmental finance from 2016 to 2020

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.techfore.2022.121639.

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