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Environmental financing: does digital economy matter?

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Sustainable development and ecological restoration are a common goal pursued by countries around the world to mitigate the collision between economic growth and the environment. Digital economy has been rather instrumental in settling this type of conflict. The study is intended to identify the relationship between digital financing and environmental financing by assessing the specificities of their temporal and industry-specific dynamics, as well as to determine the side effects that the digital economy has in terms of current environmental investments and costs. The special attention is paid to the effect of the digital economy on both total environmental financing and its components, namely, environmental investment and current environmental protection costs. The authors come up with two indicators to evaluate the impact of the digital economy, these are digital financing (direct impact) and digital capital (indirect impact). To calculate these indicators, the authors' own method is developed. The impact of the digital economy on environmental financing was tested using the least squares method with clustering of annual standard deviation and individual fixed effects. The research data were retrieved from the Federal State Statistics Service (Rosstat) of the Russian Federation for 2012–2022. Our findings show that digital financing exerts a significant positive effect on environmental financing, which indicates that two dynamic processes in the economy—digital transformation and introduction of advanced environmental digital technologies—are synchronized. The authors prove that digital investments stimulate a comparable increase in environmental investment due to the effects created by digital technologies penetrating into environmental protection technologies. We demonstrate that the level of digitalization of the population, companies and the state assessed through the digital capital index has a positive effect on environmental financing. The results of the study are of use in the sphere of public policy.

KEYWORDS

sustainable development, digital economy, environmental financing, ecological restoration, digital capital

1 Introduction

Accelerated economic growth entails significant environmental problems associated with increasing pollution and depletion of resources. In the 21st century, anthropogenic pressure has turned into the main threat to human health, survival and development across the world. Sustainable development and ecological restoration have become, therefore, a common goal that all nations are striving for to mitigate the conflict between economic growth and the environment (Lu et al., 2017; Liang and Yang, 2019). Solving environmental problems and preventing new ones require companies and the states to invest significant

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amounts of financial resources. One of the most pressing issues of environmental protection, therefore, is the search for funding. The financial mechanism of nature management characterizes the state environmental policy, which means both direct financing of environmental protection measures at the expense of the state budget, and a set of tools to stimulate private investors.

However, sustainable development is not the only trend of the 21st century. Total digitalization has underlain the economic transition from one technological paradigm to another through the massive use of digital and information and communication technologies for boosting efficiency and competitiveness. To some extent, the digital economy has resolved the conflict between economic development and environmental pollution (Limna et al., 2022; Meng and Zhao, 2022).

The extensive use of digital technologies encourages the transformation and modernization of many traditional sectors of the economy, which eases the burden on the environment and resources, and reduces energy intensity. At the same time, digital technologies utilized in the environmental protection sphere allow providing more accurate assessments of the environmental impact and more reliable forecasts. The development of digital technologies opens up a plethora of opportunities for tackling environmental problems: from creating services for efficient waste management, searching for EV charging stations, monitoring systems and collecting climate change observation data to systems capable of preventing environmental risks and predicting environmental disasters.

A considerable number of scholarly publications scrutinize the role of digital technologies in reducing global emissions. Researchers analyze industry-specific features and the ownership structure and introduce them into their models, focus on spatial aspects of digital technologies' influence, conduct research using data from various countries, regions, and cities. In this context, environmental indicators such as air and water pollution, waste generation and energy consumption are used as dependent variables. In general, the impact of the digital economy on environmental financing has been understudied.

In our research, we want to focus specifically on the issues of financing environmental and digital transitions. If digitalization and sustainable development as synchronous processes are always considered together (through specific technologies that affect each other), then no one has studied the synchronization of financing of these processes. And we see in this a number of problems that have been overlooked by researchers. For example, environmental financing, as well as digital financing, represent government and corporate expenses. But the decision to finance these processes relates to different areas—for example, in companies these are different budgets located within different areas of strategy, and in the government, these are completely different departments with their own budgets and strategies. Since financing decisions are made by different responsible groups, it is quite difficult to talk about full synchronization of digital transformation and sustainable development. In addition, we intuitively believe that the propensity for digital financing is higher than the propensity for environmental financing, since digital transformation directly affects productivity and income. Therefore, if we can prove the connection between these financial flows, it will open up new opportunities for the implementation of stimulating mechanisms of public policy. This is our research motivation.

The foregoing explains the purpose of the study, which is to identify the relationship between digital financing and environmental financing by assessing the specificities of their temporal and industry-specific dynamics, as well as to determine the side effects that the digital economy has in terms of current environmental investments and costs.

In the study, we address the following research questions:

1. Does digital financing affect environmental financing? Can we affirm that the dynamic transformation of the economy is synchronized?
2. If it is, does digital investment stimulate a comparable increase in environmental investment due to the effects created by digital technologies penetrating into environmental protection technologies?
3. Is the impact of the digital economy on environmental financing dependent on the overall level of digital transformation of companies, population and the state?

We see the only limitation of the study related to the lack of separate statistical accounting. State statistical services do not single out the costs of implementing digital environmental technologies as part of environmental financing in a separate line, nor do they allocate costs for digital technologies aimed at environmental protection as part of digital financing. We will propose a solution to this problem in the Section 4.

To answer these questions, we use evidence from the Russian Federation. Similar to other nations, the country pays great attention to sustainable development, while the unfavorable state of the environment there is among the main constraints upon long-term development. According to the Environmental Security Strategy of the Russian Federation until 2025 (approved on 19 April 2017), over 70% of the population live in poor environmental conditions and are exposed to a substantial negative impact of manufacturing, transport and other industries. In recent years, green issues, such as environmental protection and the rational use of natural resources, have been high on the agenda in the country. The Russian government actively finances environmental protection activities and creates conditions for public-private partnerships to develop in this area by transferring part of the financial burden to partner companies and private investors. This is especially true for the costs incurred in collection and disposal of waste and wastewater treatment (Table 1).

Source: Federal law of 5 December 2022 No. 466-FZ "On the federal budget for 2023 and the 2024–2025 planning period". Available at https://www.consultant.ru/document/cons_doc_LAW_433298/(accessed on 30 May 2023).

In Russia, the primary document guiding the digitalization of the environment is the Strategic Direction for Digital Transformation of Ecology and Nature Management, which was approved on 8 December 2021. This document outlines several technologies that will be implemented to enhance environmental management. Artificial intelligence will be employed to analyze monitoring data, predict hazardous weather conditions and forest fire risks, automate real-time decision-making, and identify flora and fauna in complex environments. Remote sensing of the Earth and the use of unmanned aerial vehicles will be utilized for surveying, planning efficient resource utilization, protecting

TABLE 1 Russian government expenditure on environmental protection from the federal budget in 2023 and for the 2024–2025 planning period, thousands of rubles.

	2023	2024	2025
Environmental protection - total	352,164,590.9	319,276,310.0	261,872,095.6
Waste collection, disposal and wastewater treatment	13,072,478.1	19,062,954.5	2,046,368.6
Protection of flora and fauna and their habitat	16,833,745.4	17,120,771.7	12,106,573.0
Applied scientific research in the field of environmental protection	1,122,323.1	1,091,259.6	1,129,065.5
Other issues in the field of environmental protection	321,136,044.3	282,001,324.2	246,590,088.5

natural resources and the environment, and monitoring climate change. The Internet of Things (IoT) will play a crucial role in the development of the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) observation network program, improving the efficiency of data collection and transmission from stationary and mobile observation points. Big data and analytical data processing will be used to accumulate, store, analyze, and process data within federal state information systems and digital platforms. Additionally, the concept of a digital twin will be employed to update and create a comprehensive database of natural objects, including ecosystems such as subsoil, bodies of water, forests, and wildlife habitats. This will enable better understanding and management of these natural resources. Overall, these technological advancements aim to enhance environmental monitoring, resource management, and conservation efforts in Russia.

Another solution to environmental problems is the development of geographic information systems (GISs) that are designed to collect, analyze, store and graphically interpret spatial and temporal data, as well as attributive information about the objects presented in the GIS. Owing to these systems, it is possible to rationally manage resources and, by applying new means and methods of data processing, to optimize and control their use both at the regional and federal levels.

Digital technologies are also used to automate decision-making and managerial processes in the field of environmental and natural resources management. In this framework, it is planned to create a unified federal state information system for environmental monitoring that will contain data on the state of natural objects and environmental pollution. In addition, new data analysis methods will be pioneered to more accurately and quickly assess the environmental situation and forecast possible ecological problems. The government plans to implement full digital transformation of the environmental sector. Thus, the Strategic Direction for Digital Transformation of Ecology and Nature Management is an important step towards environmental security and sustainable development in Russia.

The present study consists of the following parts. Section 2 provides a literature review to find out the conceptual and logical relationship between the indicators under analysis. In Section 3, we elaborate on research design and theoretical hypothesis. The details about the models, variables and data resources are given in Section 4. Section 5 contains the modelling outcomes and economic rationale for them. Section 6 summarizes the research results.

2 Literature review

2.1 Digital economy and sustainable development

Digital economy is an economic concept that views digital knowledge as a key factor of production and looks at modern information and communication networks as the main carrier of digital knowledge (Purnomo et al., 2022). The digital economy plays a crucial role in mitigating market imperfections, improving economic efficiency and optimizing the industrial structure. The existing definitions of the concept of digital economy are summarized by a number of researchers (Williams, 2021; Zhang et al., 2021). The core characteristics of the digital economy are systematized in (Borremans et al., 2018; Ding et al., 2021). The digital economy consists of three main components: digital infrastructure, digital technologies in economic sectors, and e-commerce. Digital infrastructure ensures the connectivity of economic agents; digital technologies and solutions transform virtually all aspects of production and consumption; and e-commerce includes the exchange of economic resources using platforms and reduces transaction costs (Akberdina and Barybina, 2022). It is worth noting that the development level of the digital economy directly correlates with the level of the material sphere. The digital economy is a superstructure over the material sector of the economy and allows increasing the efficiency of any interaction. Hence, if digital technologies are introduced in the context of the insufficient development of material production, the cumulative economic effect of digitalization will not be of decisive importance.

The digital economy in a country covers information technology, software, mobile communications, and data transmission. There is quite a lot of studies on various aspects of the digital economy in Russia (Akberdina, 2018; Basaev, 2019; Ziyadullaev et al., 2019; Belokurova et al., 2020; Gureev et al., 2020; Vlasov, 2020; Rudyk et al., 2022). The researchers note that the digital economy in Russia is developing at a high pace, transforming industries and markets and penetrating into education and intellectual activity. At that, the digital inequality of the regions and the low share of their own digital technologies serve as development constraints.

Sustainable development, green economy, circular economy and ESG-concept are the components of a worldview advocating that a just economy should be built in accordance with both social and environmental dimensions, since the economy and the environment have a tremendous mutual influence on each other (Söderholm, 2020;

D'amato & Korhonen, 2021). These concepts share a common thesis that a low-carbon, resource-efficient and socially inclusive economy should improve human wellbeing and social justice, while significantly reducing environmental threats and resource scarcity (Bouchoucha, 2021; Xie et al., 2023). The bibliometric analysis indicates that there is an upward trend in the number of research in the field of green economy, circular economy and sustainable development; however, there are country-specific differences in terminology (Ali et al., 2021). At that, all researchers tend to believe that the efficient use of resource, the circular economy, innovation, social integration, ecosystem protection, *etc.*, contribute to the coordinated development of the economy, society and the environment and the achievement of sustainable development (Ozkan et al., 2023).

Sustainability and the green economy in Russia are also deeply investigated (Bobylev and Solovyeva, 2017; Zhironkin et al., 2017; Popkova et al., 2018; Karieva et al., 2020; Tulupov et al., 2020; Lavrikova et al., 2021; Kuznetsova et al., 2022; Tagaeva et al., 2022). The researchers highlight that Russia is rich in natural resources, which has historically formed an evolution model based on commodity exports. To shift to a new paradigm of economic development, the concept of sustainability with a balanced set of economic, social and environmental components should be included in the strategic documents underlying the country's long-term development.

Researchers typically sharing similar views within each subject area, however, express serious disagreements on the *impact the digital economy has on sustainable development* (Adeshola et al., 2023). On the one hand, extensive studies have shown that the digital economy and the green economy develop in sync and positively influence each other (Wu et al., 2018; Kostoska and Kocarev, 2019; Vinuesa et al., 2020). Some works analyze the overall impact of the digital economy on the total productivity of green factors of production. Researchers emphasize that information technology can increase labor productivity and promote economic growth, which are in a positive correlation with the total productivity of green factors of production (Niebel, 2018; Nguyen et al., 2020; Wang et al., 2021; Wang et al., 2022c). A number of publications put the emphasis on the relationship between digitalization and energy consumption and conclude that digital technologies cause a decrease in energy intensity (Mughal et al., 2022; Sun, 2022). For example, it was found that with a 1% increase in the digital economy index, the number of developments in the new energy domain increases by an average of 0.2% (Wang et al., 2022a). Additionally, the digital economy not only creates conditions for clean energy to develop in countries with high carbon emissions (Wang et al., 2022b), but also helps to optimize the energy structure, increase energy efficiency (Li et al., 2021; Nikitaeva and Dolgova, 2022; Pierli et al., 2022; Xue et al., 2022; Akberdina et al., 2023) and reduce energy consumption.

On the other hand, a fairly large part of works is devoted to the inverse relationship between the digital economy and environmental pollution. For instance, researchers demonstrate that there are certain contradictions between smart digital cities and sustainable development goals (Martin et al., 2018), note that digitalization is not yet proved to be essential for reducing energy consumption and greenhouse gas emissions (Jin et al., 2018), and assume that digital equipment causes a lot of damage to the environment during production, maintenance and disposal (Kuntsman and Rattle, 2019). The main argument for the inverse relationship between the digital economy and reducing the burden on the environment is the fact that the use of digital technologies (big data, in particular) increases energy consumption (Van Heddeghem et al., 2014; Zhou et al., 2018). The researchers claim that the share of digital infrastructure in the national energy consumption can reach up to 10%–15%.

2.2 Environmental financing

Sufficient funding is a vital prerequisite for a significant improvement in the state of the environment. Strictly speaking, sustainable development should be carried out amid the simultaneous progress in financial instruments. To handle this problem, various financing models are implemented (Cui et al., 2021; Sinha et al., 2021). Environmental protection funding was initially the state's responsibility; however, in recent years, this function has been transferred to public-private partnerships leaving the state in charge of financing the relevant infrastructure (Ho and Park, 2019). In addition to PPP, the state actively encourages private investors to invest in environmental protection by providing tax incentives, grants and subsidies. Traditionally, there are two types of private investors—institutional and individual (Zhou et al., 2020; Akomea-Frimpong et al., 2022). Institutional investors are commercial banks, insurance companies, pension and public funds. Private capital is provided by interested companies. Recently, the market for green loans (Su et al., 2022) and green bonds (Tolliver et al., 2020) has been formed in the institutional segment. The evolution of the digital economy has led to the emergence of a new type of investor, i.e., crowdfunding platforms to finance environmental expenditures (Böckel et al., 2021).

In various studies, the term "environmental finance" is used as a synonym for such concepts as "green finance" (Muganyi et al., 2021; Meo and Zhao, 2022), "ecological finance" (Kihombo et al., 2021; Lee et al., 2022), "sustainable finance" (Develay and Giamporcaro, 2023) or "clean technology finance" (Madaleno et al., 2022). Originally, the term referred to the environmental economics paradigm and environmental investment. However, with the development of direct and derivative financing instruments, the growing impact of environmental problems and the tightening of environmental regulations (Cao et al., 2021; Feng et al., 2022) the scope of the term's application has gradually expanded. Hence, the concept of environmental finance will be evolving adding new research aspects over time.

Publications on environmental financing in the Russian Federation cover the full range of issues identified above, focusing on the development of a green financial market and green risks (Ziyadin et al., 2019; Tulupov et al., 2020; Tyuleneva & Moldazhanov, 2020; Altunina and Alieva, 2021).

2.3 Digital capital

The existing literature on the digital economy primarily deals with measuring its level and effects. Currently, there is no single measurement method for selecting and evaluating indicators of the digital economy. Researchers mainly evaluate the digital economy and related indicators in terms of their specific tasks. The details of these methods are beyond the scope of the given study, but it is sufficient to refer to review articles (Bukht and Heeks, 2017). We are going to consider one of the indicators of the digital economy, namely, digital capital. This phenomenon is less popular among researchers if compared to the digital economy, and there are significant differences in studies with respect to the approaches used.

The first approach addresses digital capital from the perspective of an individual and in close connection with social and cultural capital (Resnick, 2004; Seale, 2012). These studies lie in the field of sociology and explore the extent to which people are involved in the use of digital technologies. Digital capital is interpreted as an individual's digital technology ecosystem that determines how a user interacts with digital technologies. This characterizes the conditions for effective interaction between an individual and digital technologies, which he/she needs for their wellbeing in a digital society. The ability to purchase digital gadgets and software is a subset of an individual's economic capital, and the material exchange takes place in areas where ICTs are used. Digital capital manifests itself in cultural capital in the form of digital skills, knowledge and competencies (Park and Park, 2017; Vartanova and Gladkova, 2020).

The second approach examines digital capital in the context of companies' intangible assets (Crouzet and Eberly, 2019; Ayyagari et al., 2020; McGrattan, 2020; Tambe et al., 2020; Wu et al., 2020). Firms invest in both manufacturing and digital equipment to enhance their production capacity. ICT equipment (servers, routers, online shopping platforms and basic Internet software) acts as a tangible part of digital capital. In order to benefit from new technologies, digital-focused companies not only require investments in digital technologies but also in intangible assets. These intangible assets include staff training, new decision-making structures, and new business models to generate profits from digital activities (Eisfeldt and Papanikolaou, 2013; Bughin and Manyika, 2018). These investments often result in higher overall costs compared to the costs of digital technologies alone. These intangible assets make up the intangible part of digital capital. Similar to other forms of capital, digital capital can depreciate over time and needs to be replenished through additional investments. However, unlike tangible assets, the value of the intangible part of digital capital is closely tied to a specific company and is influenced by external economic conditions. As a result, the value of intangible assets tends to fluctuate more strongly than the value of tangible ICT assets, which are more easily exchangeable and have active secondary markets. As digital capital becomes an increasingly crucial component of a company's overall capital reserves, differences in digital capital among firms can explain variations in the performance of new digital-focused companies compared to older firms. These differences in digital capital can be attributed to the accumulated reserves and variations in the marginal costs of investing in digital capital. In summary, the presence and management of digital capital play a significant role in determining the success and performance of digital-focused firms in comparison to traditional firms (Tambe et al., 2020).

The third approach to investigating digital capital lies in the field of the regional economy and characterizes the extent to which digital capital of a country or region is formed. The existing studies in this domain are not numerous. A number of publications on the assessment of the country's digital capital as a combination of digital technologies and digital competencies explore its relationship with socio-economic and demographic characteristics such as income, age, education level, and place of residence, *etc.* (Ragnedda, 2018; Ragnedda et al., 2020). The techUK trade association holds a regular study of the Local Digital Capital Index (LDC Index) in the UK regions (LDCI, 2021; LDCI, , 2022). This index incorporates eight components, these are digital skills, digital technologies, data ecosystems, digital infrastructure, finance and investment, research and innovation, trade support, and cooperation. The LDC Index evaluates the impact that digital technologies can exert on the region, demonstrates its strengths and sets the direction for further development. The Index can be applied when formulating public policy to address a range of issues faced by the region and the entire country. The LDC Index also provides data to regional innovation ecosystems, including industry, government, universities and the public.

2.4 Research gap

Despite the fact that the mutual impact of digitalization and sustainable development is being studied in depth, the issues of the relationship of financial flows underlying these processes have not been investigated. Our research should fill this gap, initiate such research, and substantiate the directions for clarifying public policy.

3 Research design and theoretical hypothesis

Environmental financing consists of two components—environmental investment and current environmental protection costs. Environmental investment is investment in equipment, technologies and new facilities in a particular period to insure environmental protection. Current environmental protection costs cover annual costs incurred in many areas of environmental protection, such as expenditures on the current control of the production and consumption wastes circulation, on the maintenance of the fixed capital for environmental purposes, and R&D expenditures as far as they relate to nature protection.

We will assess the impact of the digital economy on environmental financing using two indicators, these are digital financing and digital capital. Digital financing includes digital investment, current digital costs, and digital competence costs. To calculate digital capital, we adopt the aforementioned approach, but offer our own index methodology described in Section 3 'Methods and Data'.

We believe that the mechanism for linking the digital economy and environmental financing can be represented as follows (Figure 1):

1. The effect of the digital economy on environmental financing is assessed through digital financing. Digital economy is manifested through digital technologies that are put in new equipment purchased through investments in environmental protection, as well as the associated expenses for digital competencies and the ongoing costs of maintaining digital infrastructure.

H1. The higher the share of digital financing in a company, region or country, the more likely it is that environmental financing will cover

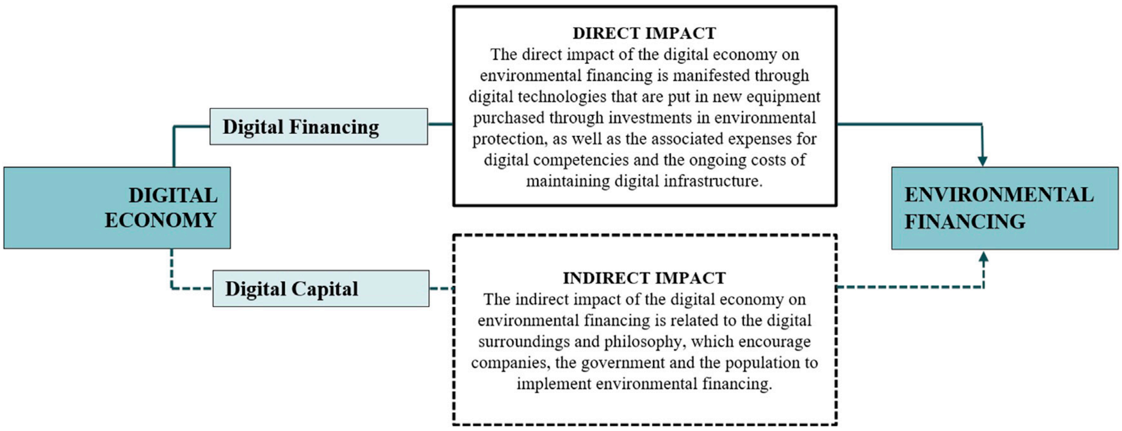

FIGURE 1
Direct and indirect impact of the digital economy on environmental financing.

expenses on new digital environmental protection technologies, and the larger the total amount of environmental financing.

Since any investments depend on companies' financial situation, profitability and risk, their dynamics will be unidirectional if investments are aimed at technological changes. Investments and current operating expenses are of a different nature, and their dynamics is determined by different factors. This thesis allows us to come up with another two hypotheses.

H2. A positive relationship of digital financing is stronger with environmental investment and weaker with current environmental protection costs.

H3. There is a strong positive relationship between digital investment and environmental investment, and the positive relationship of current digital costs and digital competence costs with environmental investment is weaker.

2. The indirect effect of the digital economy on environmental financing is associated with the formation of the necessary digital environment and worldview that stimulate companies, the state and the population to engage in environmental financing. To assess the strength of the relationship, the 'digital capital' indicator is used.

H4. Digital capital has a positive effect on environmental financing due to the cumulative synergistic effect of digitalization of the population, companies and the state.

H5. Effect of digital capital on environmental investment is more positive whereas its effect on current environmental protection costs is less positive.

4 Methods and data

4.1 Model's construction

According to the above theoretical analysis and study design, to test the impact of the digital economy on environmental financing, we will use the least squares method (LSM) with clustering of annual standard deviation and individual fixed effects. Figure 2 presents the set of the tested models.

Hypothesis H1. is tested using model M1:

$$\boldsymbol{EF_{it} = \alpha_0 + \alpha_1 DF_{it} + \alpha_2 C_t + \varepsilon_{it}} \quad (1)$$

where EF_{it} denotes environmental financing of industry i in time period t; DF_{it} is digital financing of industry i in time period t; C_t is a vector of control variables in time period t; ε_t denotes random term; α_1 and α_2 are the coefficients to be estimated.

To test hypothesis H2, models M1.1 and M1.2 are used, respectively:

$$\boldsymbol{EI_{it} = \beta_0 + \beta_1 DF_{it} + \beta_2 C_t + \mu_{it}} \quad (2)$$

$$\boldsymbol{CEPC_{it} = \gamma_0 + \gamma_1 DF_{it} + \gamma_2 C_t + \delta_{it}} \quad (3)$$

where EI_{it} denotes environmental investment of industry i in time period t; $CEPC_{it}$ is current environmental protection costs of industry i in time period t; DF_{it} is digital financing of industry i in time period t; C_t denotes a vector of control variables in time period t; μ_t and δ_t are random terms; β_1, β_2, γ_1 and γ_2 are the coefficients to be estimated.

Hypothesis H3. is tested using model M1.1.1:

$$\boldsymbol{EI_{it} = \rho_0 + \rho_1 DI_{it} + \rho_2 CDC_{it} + \rho_3 DCC_{it} + \rho_4 C_t + \tau_{it}} \quad (4)$$

where EI_{it} denotes environmental investment of industry i in time period t; DI_{it} denotes digital investment of industry i in time period t; CDC_{it} is current digital costs of industry i in time period t; DCC_{it} is digital competence costs of industry i in time period t; C_t denotes a vector of control variables in time period t; τ_t is random term; ρ_1, ρ_2, ρ_3 and ρ_4 are the coefficients to be estimated.

For testing hypothesis H4, model M2 is designed:

$$\boldsymbol{EF_{it} = \chi_0 + \chi_1 DC_t + \chi_2 C_t + \omega_{it}} \quad (5)$$

where EF_{it} denotes environmental financing of industry i in time period t; DF_{it} is digital capital in time period t; C_t is a vector of control variables in time period t; ω_t denotes random term; χ_1 and χ_2 are the coefficients to be estimated.

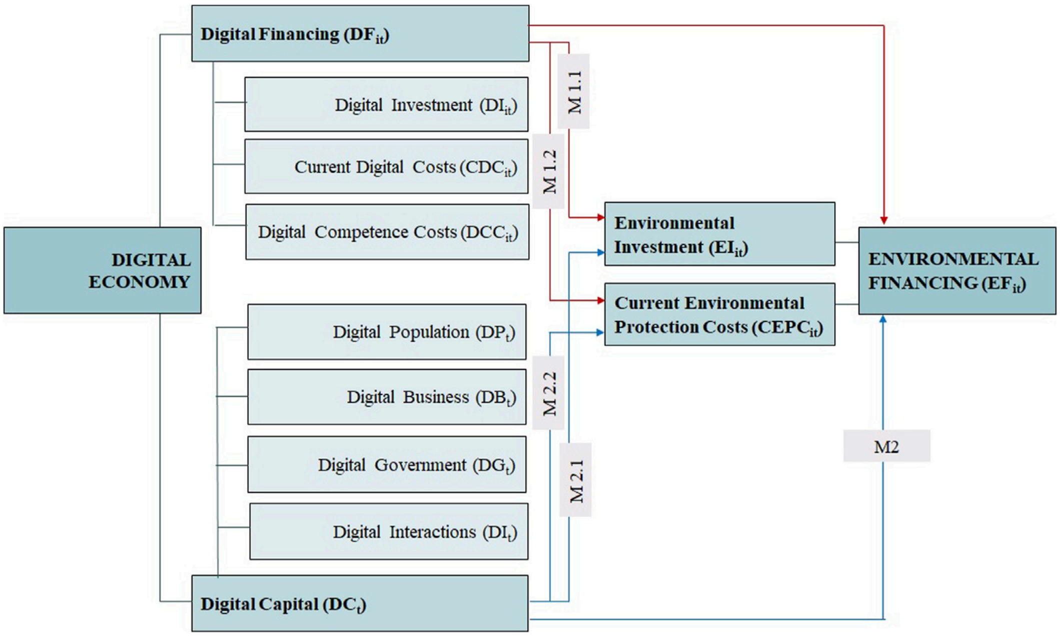

FIGURE 2
A set of models of the impact of the digital economy on environmental financing.

As indicated above, we offer our own index methodology to evaluate digital capital:

$$DC_t = \sqrt[4]{DP_t \cdot DB_t \cdot DG_t \cdot DI_t} \tag{6}$$

where DC_t is digital capital index in time period t; DP_t is digital population index in time period t; DB_t is digital business index in time period t; DG_t denotes digital government index in time period t; DI_t is digital interaction index in time period t.

Similar approach to integrating sub-indices into a composite index produced a positive outcome in the case of the digital space index (Akberdina et al., 2022).

The first sub-index DP_t describes digital competencies of the population that are assessed through the following indicators: the number of mobile broadband Internet access subscribers per 100 population, the share of households with broadband Internet access, the share of the population that are active Internet users, the number of graduates in the program Computer Science and Computer Technology per 10,000 population, and the share of people employed in the ICT sector in the total number of the employed.

The second sub-index DB_t is related to the level of companies' digital transformation. The following indicators are applied to assess it: the share of organizations that provided additional training for employees in the field of ICT, the volume of investments in ICT, the share of organizations using Internet access at a speed of at least 2 Mbps, the share of organizations having special software to manage the procurement of goods (works, services), the share of organizations having special software to manage the sales of goods (works, services), the share of organizations using ERP systems, the share of organizations using CRM systems, and the share of organizations using electronic document management systems.

The third sub-index DG_t shows the extent to which digital technologies have penetrated the sphere of public administration and is assessed using the following indicators: the share of public authorities and local governments using the Internet at a speed of more than 256 Kbps, the share of public authorities and local self-governments with a data transfer rate of at least 2 Mbps, the share of public authorities and local self-governments using electronic digital signature means, and the share of public authorities and local self-governments utilizing electronic document management systems.

The fourth sub-index DI_t reflects the extent to which the interactions between the population, companies and the state are digitized. The following indicators are applied to assess it: the share of public authorities and local governments using automatic data exchange, the share of public authorities and local governments providing access to databases, the share of orders for state and municipal needs placed via electronic trading platforms, the share of the e-document management system in the interaction between public authorities, the share of organizations using the Internet to receive certain types of state and municipal services, the share of organizations using electronic data interchange between internal and external information systems, the share of organizations placing orders for goods (works, services) on the Internet, the share of organizations receiving orders for goods (works, services) via the Internet, the share of organizations using digital platforms, the share of the population using the Internet to get state and municipal services, and the share of the population using the Internet to order goods and (or) services.

The indicators of the sub-indices were normalized. The maximum value for each indicator over a period of time was equated to one, and the values for the remaining years were normalized in relation to it.

TABLE 2 Description of PBI_t variables.

Type	Name	Code	Measure unit	Data path
Dependent	Environmental Financing	EF_{it}	rubles	https://rosstat.gov.ru/storage/mediabank/Rashod_oxr.xls
Dependent	Environmental Investment	EI_{it}	rubles	https://rosstat.gov.ru/storage/mediabank/Zatrat_2022.xls
Dependent	Current Environmental Protection Costs	$CEPC_{it}$	rubles	https://rosstat.gov.ru/storage/mediabank/oxr_zatr_4.xls
Independent	Digital Financing	DF_{it}	rubles	https://rosstat.gov.ru/storage/mediabank/3-inf_2015(1)(1).rar
Independent	Digital Investment	DI_{it}	rubles	https://rosstat.gov.ru/storage/mediabank/3-inf_2016(1)(1).rar
Independent	Current Digital Costs	DCC_{it}	rubles	https://rosstat.gov.ru/storage/mediabank/3-inf_2017(1)(1).rar
				https://rosstat.gov.ru/storage/mediabank/3-inf_2018(3).rar
Independent	Digital Competence Costs	CDC_{it}	rubles	https://rosstat.gov.ru/storage/mediabank/3-inf_2019.rar
				https://rosstat.gov.ru/storage/mediabank/3-inf_2020(2).rar
				https://rosstat.gov.ru/storage/mediabank/3-Inf_2021.rar
Independent	Digital Capital Index	DC_t	index	calculated
Independent	Digital Population Index	DP_t	normalized value	https://rosstat.gov.ru/storage/mediabank/monitor.xlsx
Independent	Digital Business Index	DB_t	normalized value	https://rosstat.gov.ru/storage/mediabank/monitor.xlsx
				https://rosstat.gov.ru/storage/mediabank/Ikt_org(1).xlsx
Independent	Digital Government Index	DG_t	normalized value	https://rosstat.gov.ru/storage/mediabank/monitor.xlsx
Independent	Digital Interaction	DI_t	normalized value	https://rosstat.gov.ru/storage/mediabank/monitor.xlsx
Control	GDP *per capita*	GDP_t	rubles	https://rosstat.gov.ru/storage/mediabank/VVP_na_dushu_s1995-2022.xls
Control	Research and Development Costs	$R\&D_t$	rubles	https://rosstat.gov.ru/storage/mediabank/nauka-5.xlsx
Control	Private Business Investments	PBI_t	rubles	https://rosstat.gov.ru/storage/mediabank/Invest-fs.xls

Finally, hypothesis H5 is tested using models M1.2 and M2.2:

$$\boldsymbol{EI_{it} = \nu_0 + \nu_1 DC_t + \nu_2 C_t + \varphi_{it}} \quad (7)$$

$$\boldsymbol{CEPC_{it} = \eta_0 + \eta_1 DC_t + \eta_2 C_t + \psi_{it}} \quad (8)$$

where EI_{it} is environmental investment of industry i in time period t; $CEPC_{it}$ denotes current environmental protection costs of industry i in time period t; DC_t is digital capital in time period t; C_t is a vector of control variables in time period t; φ_t and ψ_t are random terms; ν_1, ν_2, η_1 and η_2 are the coefficients to be estimated.

4.2 Variables and data sources

Based on the research purpose and data availability, we have developed dependent variables, main independent variables, control variables, and intermediate variables. Their specific values, calculation methods and data sources are presented in Table 2.

The study used data from the Federal State Statistics Service of the Russian Federation (Rosstat) on environmental protection expenditures for 2012–2022 by industry, including investment and current costs. In the research, the data are given by types of industry-specific economic activity—in aggregate (sections B, C, D, E according to the OKVED-2 classifier [OKVED-2 is the Russian National Classifier of Types of Economic Activity]) and in detail (industry sectors—decimal codes according to the OKVED-2 classifier).

To perform regression modeling of the relationship between environmental financing and digital financing, the data for 2015–2021 were taken, since the statistics on digitalization by type of industry expenses has been collected only since the approval of the state program Digital Economy of the Russian Federation. To carry out the regression assessment of the relationship between environmental financing and digital capital, data for 2012–2022 were used. The indicators for calculating the digital capital index and sub-indices are presented in the Consolidated Monitoring of the Development of the Information Society in the Russian Federation, provided by the Federal State Statistics Service of the Russian Federation.

5 Results and discussion

5.1 Digital financing and environmental financing

The first group of the research models dealt with the direct relationship between digital financing and environmental financing. Table 3 presents empirical results based on panel data for 31 Russian industries for 7 years (2015–2021). As we can see, the main model M1 (Eq. 1) gives quite good results: the regression coefficient of the impact of digital financing (DF_{it}) on environmental financing (EF_{it}) is positive and passed the test for significance at the 1% level.

We suppose that in this case the effect of digital technologies penetrating into environmental protection technologies is triggered.

TABLE 3 Effects of the digital economy on environmental financing.

Independent	Model 1	Model 1.1	Model 1.2	Model 1.1.1	Model 2	Model 2.1	Model 2.2
	EF_{it}	EI_{it}	$CEPC_{it}$	EI_{it}	EF_{it}	EI_{it}	$CEPC_{it}$
DF_{it}	0.423*** (12.07)	0.739*** (42.19)	0.290*** (3.13)	—	—	—	—
DI_{it}	—	—	—	0.428*** (54.33)	—	—	—
DCC_{it}	—	—	—	0.107*** (9.78)	—	—	—
CDC_{it}	—	—	—	0.239*** (11.04)	—	—	—
DC_t	—	—	—	—	0.018*** (10.73)	0.139*** (22.16)	0.007*** (1.25)
GDP_t	0.008*** (10.12)	0.009*** (11.56)	0.011*** (21.01)	0.007*** (12.77)	0.007*** (3.13)	0.006*** (3.45)	0.007*** (2.11)
$R\&D_t$	0.001*** (6.01)	0.001*** (7.12)	0.001*** (1.12)	0.001*** (5.17)	0.001*** (0.12)	0.004*** (0.17)	−0.001*** (0.11)
PBI_t	0.003*** (18.47)	0.003*** (33.56)	0.003* (12.85)	0.007** (28.19)	0.007** (8.42)	0.007** (10.01)	−0.012** (1.76)
const	0.042 (2.08)	0.019 (2.89)	0.007 (1.18)	0.029 (2.12)	0.097** (7.44)	1.307** (12.06)	0.059** (2.06)
R^2	0.815	0.854	0.561	0.848	0.712	0.789	0.442
N	217	217	217	217	341	341	341

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$; the values in parentheses are t values.

Digital technologies such as the Internet, the IoT, artificial intelligence, big data, digital twins, *etc.*, are widely used in environmental protection, which changes resource consumption patterns, pollution reduction, and higher energy efficiency. These technologies are instrumental in analyzing big data obtained through environmental monitoring, automating management decision-making in real time, and predictive forecasting of potentially hazardous natural phenomena and objects. Owing to the use of GISs, Earth space sensing data and unmanned observation, it possible to control landfills, identify flora and fauna objects, *etc.* The effect of the digital economy is also evident when solving any engineering and environmental problem. Software for design and automation of technological preparation of production is of great importance for cleaner production to progress. Increasingly scrupulous attention is paid to the latest achievements in artificial intelligence and neural networks applied to produce optimal technological solutions, i.e., to optimize resource consumption, reduce emissions of harmful substances, and cut down energy consumption.

On the other hand, there is a substitution effect: outdated production technologies are replaced by new digital solutions, which ultimately leads to a significant decrease in environmental pollution and resource savings in industry. This, in turn, reduces the need for environmental facilities construction funding and lowers current environmental protection costs. For example, industrial robots replace human labor for automated production, intelligent design improves the efficiency of allocation of production factors and productivity. Digital technologies also contribute to reducing the volumes of raw materials required. With electronic sensors of various sizes, virtually any change in the production system's operating state can be monitored. This allows not only tracking CO_2 emissions, but also controlling the level of emissions related to the company's entire value chain. The effects of penetration and substitution are manifested in different growth rates of digital financing and environmental financing. As evidenced by the case of Russia, digital financing is increasing annually at a faster pace than environmental financing. This led to the fact that over 7 years the share of digital financing in GDP increased 1.8 times, while the rise in the share of environmental financing in GDP was only 1.3 times (Figure 3). This absolutely does not mean that the digital economy in Russia is prioritized over sustainable development; this is merely a manifestation of the abovementioned effects. Thus, we can conclude that hypothesis H1 has been confirmed.

Models M1.1 and M1.2 (Eqs 2, 3) were developed to test hypotheses about the impact of digital financing on the elements of environmental financing, namely, environmental investment and current environmental protection costs. Table 3 demonstrates the situation that we had predicted. There is a sustainable positive relationship between digital financing (DF_{it}) and environmental investment (EI_{it}). At the same time, when evaluating the relationship between digital financing (DF_{it}) and current environmental protection costs ($CEPC_{it}$), we can see that the regression coefficient is a positive number of 0.290, but it fails the test for significance indicating that there is no relationship between the indicators.

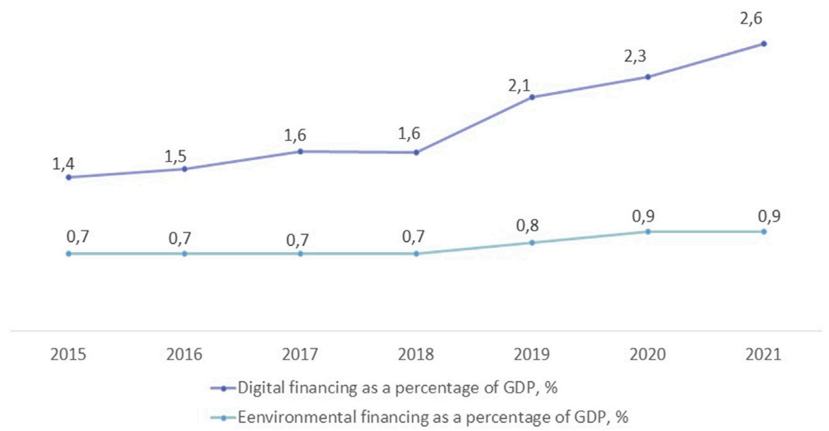

FIGURE 3
Digital financing and environmental financing as a percentage of GDP in the Russian Federation, %.

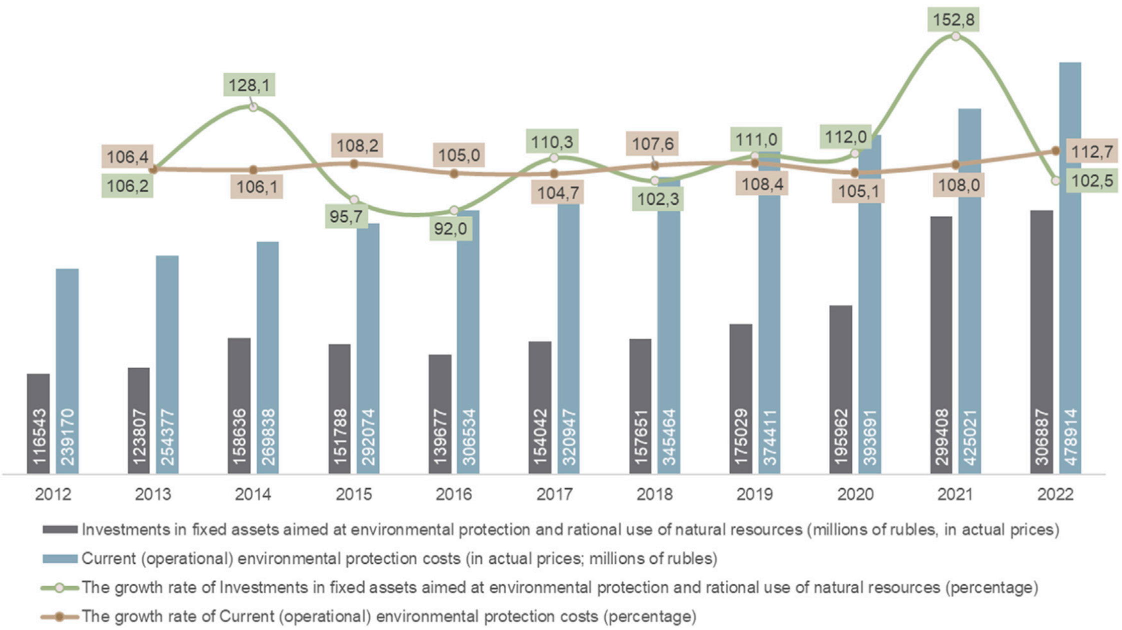

FIGURE 4
Dynamics of environmental investment and current environmental protection costs in the Russian Federation.

We argue that environmental investment and current environmental protection costs are of a different nature and determined by different factors. This is clearly illustrated in Figure 4.

The dynamic graphs of environmental investment and current environmental protection costs are configured in a completely manner. Current environmental protection costs are related to production volumes and resource consumption. Digital technologies have little effect on the costs associated with previous technological solutions. We believe that environmental investment is determined by the willingness of companies to invest and the availability of sufficient funding. Any investment in technology, therefore, will have unidirectional dynamics and a close statistical relationship. These arguments, in our view, support hypothesis H2.

Model M1.1.1 (Eq. 4) is a variation of model M1.1 and supposed to reveal the relationship of environmental investment (EI_{it}) with digital financing components, such as digital investment (DI_{it}), current digital costs (DCC_{it}) and digital competence costs (CDC_{it}). All the independent variables exert a positive effect on environmental investment, but only digital investment is of high significance, which confirms hypothesis H3. Digital financing is unevenly distributed across different industries. Our study has shown that 75% of the funds allocated for digitalization were distributed between 10 industries (in OKVED, industry covers more than 30 types of activities). Among the sectors leading in investment in industry digitalization are the energy industry, production of petroleum products, gas and oil production, metallurgy and production of metal products, electronics and machine tool

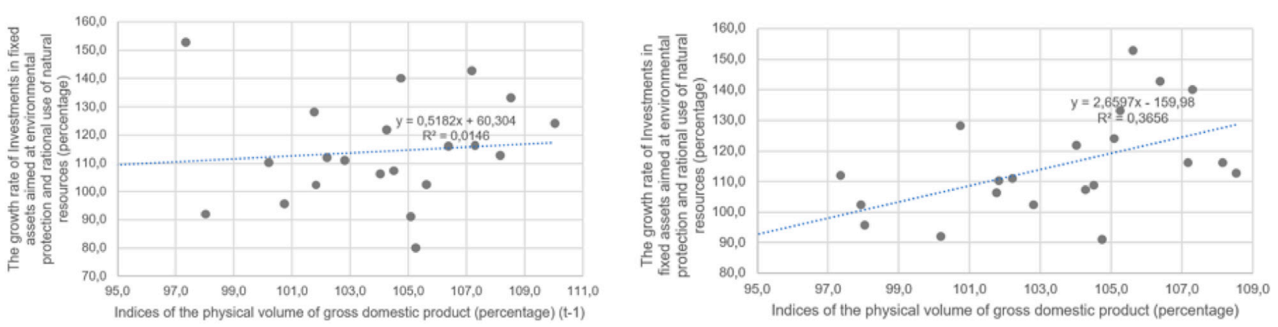

FIGURE 5
Dependence of environmental investment and GDP with a 1-year lag and without a time lag.

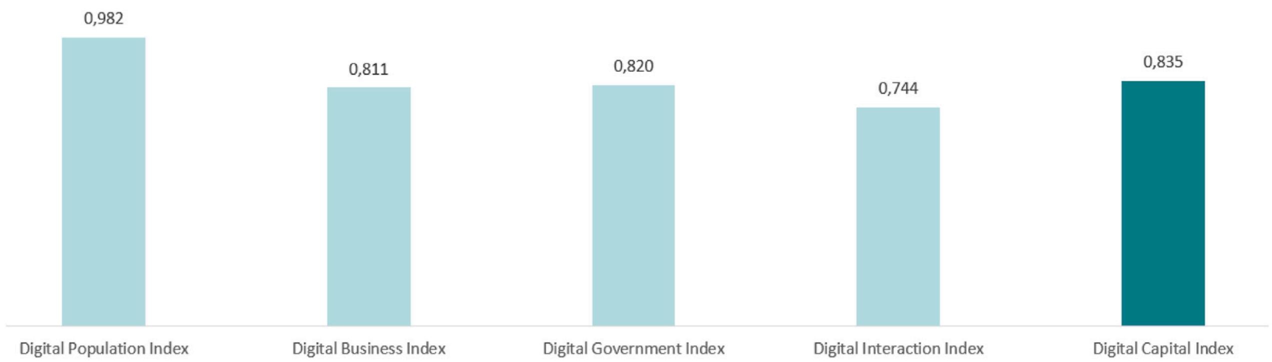

FIGURE 6
The digital capital index and its components in the Russian Federation in 2022.

manufacturing. At that, it is these industries that generate the main investment inflow in new environmental technologies and set environmental goals.

However, we prove that there is a relationship between environmental investment and GDP, but it is rather weak. Moreover, this relationship is significant only in the regression without a time lag, while a 1-year lag notably worsens the regression values (Figure 5).

In 2021, we analyzed the structure of digital financing in Russia. Of the total funds allocated for digital transformation in industry, 72% were directed to internal expenses, such as the purchase of information and communication equipment, software, staff training, *etc.* The remaining 28% of the budget was allocated to external expenses, such as digital equipment rental, software, technical support, and database access. The internal costs of digital transformation were involved in the acquisition of digital machinery and equipment, and 40.2% of these were associated with the purchase of computers and office equipment. However, the share of digital production equipment purchases remained small. Software accounted for 22% of the total domestic digitalization budget in 2021. Employee training comprised just 3% of all internal digital transformation spending. In industry, there are practically no costs incurred in the formation of digital context. Thus, the internal funds for digital transformation exceed the external ones, and most of them are aimed at purchasing hardware and software. Employee training and creating digital context in industry remain less significant expenses.

5.2 Digital capital and environmental financing

In the second part of our study of the relationship between the digital economy and environmental financing, we applied the digital capital index, for which we had previously proposed a definition and an assessment method. The digital capital index characterizes the environment, where technological segments of traditional industries develop. To assess the impact of the digital capital index (DC_t) on environmental financing (EF_{it}), we substantiated model M2 (Eqs 5, 6) and related models M2.1 and M2.2 (Eqs 7, 8), i.e., the impact of the index on environmental investment (EI_{it}) and current environmental protection costs ($CEPC_{it}$). The results of modelling are presented in Table 3. As can be seen, the regression coefficients and their significance are worse than models including digital financing; however, there is an overall positive relationship. Models M2 and M2.1 showed a more significant statistical relationship, which can be due to the fact that current environmental protection costs are in principle insensitive to anything other than production volumes.

The digital capital index has an indirect impact due to the cumulative synergistic effect of digitalization of the population, companies and the state. As follows from Figure 6, in 2022 the digital capital index in Russia was 0.835 out of the maximum possible value of 1. If the digital population index is close enough to the maximum value, and the digital business index and the digital government index are 18%–19% behind the maximum value, then the digital interaction index remains at a relatively low level of 0.744. With the growing importance of factors affecting the digital interaction index (e.g., the share of companies receiving orders via the Internet, the share of companies using digital platforms, the share of the population using the Internet to order goods and services, *etc.*), its contribution to the digital capital index will increase, so will the importance of the environmental financing index. These arguments support hypotheses H4 and H5.

6 Discussion

Digital transformation is a key factor for Russia in changing the technological structure of the economy and preserving the environment. Considering the importance of the digital economy in ensuring sustainable development, the present research has focused on the role of the digital economy in not only reducing the anthropogenic load on the environment, but in environmental financing, which, among other things, characterizes the technological renewal of this area. Having conducted the study, we answered the posed questions and arrived at the following conclusions.

Firstly, we found that digital financing has a significant positive impact on environmental financing, which indicates that the two dynamic processes in the economy—the digital transformation of the economy and the introduction of the latest digital technologies in the field of environmental protection—are synchronized. Digital technologies can be used to create innovative solutions aimed at reducing emissions of harmful substances and improving the environmental efficiency of production. For example, the use of sensors and the control system can help improve air and water quality, as well as reduce greenhouse gas emissions.

Secondly, we proved that digital investment stimulates a comparable increase in environmental investment due to the effects of digital technologies penetrating into environmental technologies. Investment in digital technologies has the potential to improve environmental monitoring, analyze pollution and resource efficiency data, and work out innovative solutions to lessen adverse environmental impacts.

Thirdly, we demonstrated that the level of digitalization of the population, companies and the state and the strengthening of the digital environment for interactions have a favorable effect on environmental financing. We introduced the digital capital index and traced the logic of its impact on environmental financing. It was found that digital involvement of the population stimulates the dissemination of information and awareness of sustainable development methods and environmentally friendly technologies; it also encourages active participation in crowdfunding platforms in support of environmental initiatives. Digital technologies in public administration can be used to create platforms for monitoring and managing various aspects of environmental protection, such as air, water and soil quality. This makes it possible to quickly detect problems and take action to resolve them, thus, minimizing the negative impact on the environment. Digitalization of production business processes allows the optimal use of material and human resources, granting the industry the opportunities to achieve sustainable development goals.

7 Discussion

The findings of our study are of special interest for public authorities. By creating conditions for a deep digital transformation of the economy, governments generate a significant demand for digital financing, which in turn increase the penetration of digital technologies into the field of ecology and stimulates environmental financing. One of the domains, where these results can be of use, is the development of the renewable energy sector. Digital technologies can make production processes and the use of renewable energy sources significantly more efficient. For example, sensors and the monitoring system allow optimizing the operation of solar and wind power plants, analyzing energy production data and predicting the consumption level. This will enhance the efficiency of using renewable energy sources and mitigate the negative impact on the environment.

Moreover, digital financing can contribute to the introduction of eco-friendly projects and initiatives. By attracting investments via digital platforms, the state can support the development and implementation of new technologies aimed at reducing greenhouse gas emissions, improving air and water quality, and the sustainable use of natural resources. Such projects may include the design of energy efficient technologies, the creation of waste management systems and sustainable agriculture.

Another fundamental aspect of digital financing is to ensure financial inclusion and access to financial services for all segments of the population. Digital platforms can provide small and medium-sized businesses and the population with limited financial resources with access to loans, investments and other financial instruments. This will improve the economic situation in regions and raise the standard of living of the population.

Thus, the results of our study can be widely used in public policy. The progress in digital financing and environmental financing can contribute to the sustainable development of the economy, reduce the damaging effect on the environment and boost the living standards of the population. The state should actively support and accelerate the development of digital technologies and eco-friendly projects to ensure a sustainable future for all.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

VA: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing–original draft, Writing–review and editing. YL: Conceptualization, Funding acquisition, Methodology, Resources, Writing–review and editing. MV: Data curation, Investigation, Visualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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