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The impact of green technology innovation on global value chain upgrading in China's equipment manufacturing industry

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In recent years, China's equipment manufacturing industry has been actively embedded in the global value chain (GVC), but pollution emission has become an important factor hindering the industry from climbing to the high-end link of GVC. How to break through this restriction through green technology innovation is exactly urgent for the Chinese government and manufacturers. Therefore, using the panel data of China's equipment manufacturing industry and its subsectors from 2007 to 2019, this paper constructs an econometric model to investigate the impact of green technology innovation on the GVC upgrading, and further examines the mediating effect through stepwise regression method. The results show that for the full samples of China's equipment manufacturing industry, there is a U-shaped relationship between green technology innovation and the promotion of GVC status; and for basic metals and metal products manufacturing subsector and transport equipment manufacturing subsector, the conclusion is same with the whole industry; but for machinery equipment manufacturing subsector and electrical, electronic and optical equipment manufacturing subsector, the trend is opposite, that is, an inverted U-shaped relationship which first rises and then declines. Additionally, green technology innovation in China's equipment manufacturing industry can promote GVC upgrading by reducing its dependence on GVC, optimizing export trade, reducing pollution costs, and promoting green product and process innovation. Based on the above, this paper finally proposes targeted policy implications to provide theoretical basis and experience reference for China's equipment manufacturing industry to promote the GVC upgrading through green technology innovation.

KEYWORDS

equipment manufacturing industry, green technology innovation, global value chain upgrading, mesomeric effect, upstream degree

1 Introduction

As a basic and strategic industry, equipment manufacturing industry's position in the global value chain (GVC) directly affects a country's profit distribution and value-added opportunities (Lu, 2017). In recent years, China's equipment manufacturing industry has been embedded in GVC by relying on its advantages such as population and resource endowment (Xu et al., 2015). However, compared with developed countries, China's equipment manufacturing industry is engaged in low-end expansion and low value-added production, resulting in the loss of core technologies and the lack of innovation ability (Li et al., 2020a). In addition, the "low-end locking" and "high-end blocking" in GVC dominated by developed countries have formed obstacles for China's equipment manufacturing industry to jump to the high-end links, weakening China's initiative and discourse power in international trade (Li et al., 2020b). Meanwhile, China has already become the world's largest carbon emitter (Chen and Yin, 2022). Rapid development driven by large-scale use of disposable, high-emission energy sources such as oil and coal are predatory and comes at the expense of the environment (Dong et al., 2018; Li et al., 2021). Extensive economic development model has led to severe natural environmental problems in China, and the environmental carrying capacity has reached the upper limit. It is no longer possible to gain comparative advantages by relying on demographic dividend and resource endowment, and the huge energy consumption leads to a gradual shortage of resources. China's economic rise is burdened by weak growth and severe pollution problems (Zhang and Da, 2015; Wang J et al., 2020).

In this context, resource and environmental rigidity have become important factors restricting China's economic development, while breaking the traditional economic growth mode is more dependent on green technology innovation (Yu et al., 2021). The environmental policies such as "Made in China 2025", "Carbon Peak" and "Carbon Neutral" issued by the Chinese government also mentioned the importance of green technology innovation (Wang S et al., 2020; Wang et al., 2021a). Compared with pure technology innovation, green technology innovation focuses more on environmental protection by replacing the original inherent production process and form with green technology, so as to reduce the environmental pollution caused in the production process and break the green trade barriers set by developed countries (Bi et al., 2015; Zou et al., 2022). With the gradual transformation of the world economic growth pattern and the rapid development of science and technology, it has become the necessary path for the China's equipment manufacturing industry to actively participate in the international labor division and gain a jump on the GVC position (Wang et al., 2021b). Therefore, how to promote the GVC upgrading by carrying out green technology innovation has become a pressing matter of the moment for China's equipment manufacturing industry.

Over the last decade, a number of research works regarding green technology innovation in the process of GVC embedding for developing countries have been undertaken (Olson, 2013; Yan et al., 2016; Song and Wang, 2017; Sun et al., 2020a). However, most of them mainly reflect the impact of the whole country or manufacturing industry rather than more detailed industry from the perspective of focusing on industry pertinence and heterogeneity. Therefore, this paper attempts to fill the research gap by taking the equipment manufacturing industry and its subsectors as the research object and explore the role and transmission path of green technology innovation in improving the status of GVC. The results could provide the reference for solving the relationship between economic development and ecological environment and help China's equipment manufacturing industry seize the green trade market, break the green trade barriers set by developed countries, and enhance the position of GVC.

The remainder of this paper is structured as follows. The second part explains the econometric models, indicators, and data. Subsequently, the third part presents the regression analysis and finally, the fourth part presents the conclusion and policy implications.

2 Literature review

Compared with pure technology innovation, green technology innovation pays more attention to not only economic development but also environmental protection. In recent years, relevant studies begin to highlight on the effect of green technology innovation and divide it into inhibition and promotion.

On the one hand, most scholars believe that the restraining effect of green technology innovation can be divided into crowding-out effect, R&D risk effect and low-end locking effect. First of all, the green technology innovation needs to invest more funds, and firms will invest in green energy technologies only if these investments have an economic pay-off (Stucki, 2019). However, in order to meet the requirements of strict environmental regulations established by the government, green technology innovation will generate compliance costs at the initial stage of implementation, that is, increase the investment in pollution control (Gray and Shadbegian, 2019). This will cause the investment of actual production to be crowded out and soon increase the total cost, which will reduce the productivity and market competitiveness of enterprises (Bao and Chai, 2022). Second, R&D risk effect refers to the uncertainty of emerging green products, processes and technologies and the uncertainty of the external environment when enterprises carry out green technology innovation. Therefore, enterprises with weak risk tolerance tend to operate conservatively in order to avoid risks, thus hindering their sustainable development (Hasan and Habib, 2017). Finally, the low-end locking effect refers to that in the context of the GVC, if the developing countries want to promote the upgrading through green technology innovation, the developed countries will use various means to control and hinder the enterprises of the developing countries from carrying out green technology innovation, thus forcing the developing countries to be "locked" in the production and assembly links of the low-end (Zhang and Zheng, 2017).

On the other hand, most scholars believe that the promotion effect of green technology innovation mainly includes innovation compensation effect, energy saving and emission reduction effect and market demand effect. First of all, the innovation compensation effect means that in the long run, green technology innovation carried out by the reasonable environmental regulations encourage enterprises to provide greener, more environmentally friendly and low-carbon products, which is conducive to the development of green economy (Xu and Zhang, 2020). Secondly, the energy saving and emission reduction effect refers to that enterprises improve energy efficiency and reduce pollution emissions from the whole life cycle through green technology innovation. This could useful to innovate clean energy, green products and processes and reduce environmental pressure in the whole production process, which can realize the development of green economy (Li et al., 2022). Finally, the market demand effect refers to that while the market demand for green products increases, enterprises establish a green image and occupy the green market in order to form a good reputation and gain social recognition. This will help enterprises maintain long-term competitiveness in market competition, achieve core green technology breakthroughs through green technology innovation, and provide more green products from the whole life cycle (Guo and Shi, 2022).

On the basis of the above research around the economic effects of green technology innovation, some scholars began to study the relationship between green technology innovation and GVC and highlight their importance for the effective manufacturing (Marchi et al., 2013; Costantini et al., 2017; Yin et al., 2022). The research of Song and Wang (2017) shows that participation in the GVC can considerably improve the green technology levels in all enterprises, except state-owned ones. And Song et al. (2018) reach further conclusions using enterprise panel data, that the deeper the integration into the global supply chain, the looser the financing environment would be, and the stronger the green innovation abilities of the enterprises. The research of Meng et al. (2022) also highlights that increased GVC participation leads to improved green innovation performance of Chinese firms. However, Sun et al. (2020b) emphasized that although the development of green technology in manufacturing industry must rely on technological innovation, the process of implementing green innovation is full of high uncertainty and risk. More specifically, Sun et al. (2020a) summarizes and identifies the risk of green innovation in the manufacturing industry into four major kinds and 31 factors, based on the perspective of the global value chain. Therefore, some scholars find that the impact of green technology innovation on the GVC may be non-linear. Song and Wang (2018) perform a multi-index multi-factor constitutive model based on a sample of 468 Chinese industries and draw the conclusion that there is a U-shape relationship between green technology progress and comparative advantages. Wang S. et al. (2021)study the relationships among the degree of participation in GVC, technological progress, and environmental pollution from the perspective of industries in developing countries and find that there is a value chain threshold and only when the degree of participation in a value chain is higher than the threshold, technological progress can reduce emissions.

Relevant research on the effects of green technology innovation is relatively rich and lays a solid foundation for the study on the relationship between green technology innovation and GVC. However, most of the existing literatures have studied how participation in the GVC affects green technology innovation, but the reverse research is lacking. In particular, how green technology innovation in equipment manufacturing industry affects GVC upgrading has not attracted enough attention. The transmission path between green technology innovation and GVC upgrading is still unclear. Therefore, to fill the research gaps, this paper explores the effects of green technology innovation on GVC upgrading of China's equipment manufacturing industry and its subsectors by firstly constructing a baseline regression model. Subsequently, some mediating variables and the stepwise regression method are introduced to verify the impact paths of green technology innovation on GVC upgrading. According to the empirical results, some policy implications are put forward to promote green technology innovation of China's equipment manufacturing industry and realize GVC upgrading, for reference by government departments and enterprises.

3 Research and data methodology

3.1 Division of GVC upgrading direction for subsectors

This paper selects China's equipment manufacturing industry and its subsectors as the research object. Considering the industry classification standards of different databases, the equipment manufacturing industry involved in this paper can be divided into four subsectors, namely basic metals and metal products manufacturing subsector (C12), machinery equipment manufacturing subsector (C13), electrical, electronic and optical equipment manufacturing subsector (C14), and transport equipment manufacturing subsector (C15).

For the equipment manufacturing industry, the GVC upgrading refers to the improvement of the status of international division of labor, which is mainly manifested by the improvement of value-added ability and control ability. Based on the theory of "binary drive", the producer-driven industries should take the upward climb of the GVC as the direction of industrial upgrading, and the purchaser-driven industries should pursue the downward climb of the GVC. This is consistent with the description of the smile curve, that is, the division of labor at both ends of the GVC are of a higher status, and both the upstream and downstream can be the choice of the upgrading direction for different industries. Therefore, it is the primary procedure of this study to determine the GVC upgrading direction of the four equipment manufacturing subsectors, which can provide the basis for the subsequent subsector heterogeneity analysis.

To achieve this, this paper measures the industrial embedding position and GVC upgrading using the indexes of upstream degree (U) and export technology complexity (TSI). The higher the upstream degree index, the closer the industry is to the upstream position in the global value chain; and the higher the export technology complexity index, the stronger the industry's value-added ability and control ability, and the higher the GVC upgrading. By examining the impact of upstream degrees in different subsectors on the GVC upgrading, this paper subdivides the four subsectors into three groups: upstream leading group, downstream leading group and mixed leading group.

In the upstream leading group, the more to be near upstream position of the production chain, the industrial ability to obtain value-added stronger, namely that the upstream degree index has a significant promoting effect on the export technology complexity index, and subsectors in this group can enhance its GVC position and facilitate upgrading by moving closer to the upper reaches of the GVC; On the contrary, the upstream degree index has a significant inhibitory effect on the export technology complexity index in the downstream leading group, since subsectors in this group need to promote GVC upgrading by approaching the downstream of the GVC; And if there is no obvious correlation between the two indexes, it indicates that there are multiple high value-added links in the GVC for this subsector to improve the position of international labor division, who belongs to the mixed leading group.

The measurement method of the index of upstream degree (U) refers to Antràs et al. (2012), who proposed that this index can be used to measure the weighted average distance between each link in the GVC and the final product, and to reflect the position of the industry in participating in the international labor division. The calculation formula is shown as follows.

$$\boldsymbol{U_i} = 1 \times \frac{\boldsymbol{F_i}}{\boldsymbol{Y_i}} + 2 \times \frac{\sum_p \boldsymbol{d_{ip} F_p}}{\boldsymbol{Y_i}} + 3 \times \frac{\sum_p \sum_k \boldsymbol{d_{ik} d_{kp} F_p}}{\boldsymbol{Y_i}} + 4 \times \frac{\sum_p \sum_k \sum_l \boldsymbol{d_{il} d_{lk} d_{kp} F_p}}{\boldsymbol{Y_i}} + \cdots \quad (1)$$

where i, p, k and l stand for sectors with input-output linkages. d_{ip} represents the consumption of intermediate goods in sector i for each unit of product provided by sector p; F_p denotes the final products produced by sector p; Y_i denotes the value of gross output by sector i. The higher the upstream degree, the farther the sector i is from the final product. Based on the above, this paper constructs an econometric model with upstream degree (U) as the core explanatory variables as well as export technology complexity (TSI) as the explained variable to identify the upgrading direction of four subsectors of equipment manufacturing industry, shown as follow.

$$\boldsymbol{TSI_{i,t}} = \boldsymbol{\theta_0} + \boldsymbol{\theta_1 U_{i,t}} + \boldsymbol{\theta_2 CV_{i,t}} + \boldsymbol{\varepsilon_{i,t}} \quad (2)$$

where $CV_{i,t}$ stand for control variables, which mainly include: 1) economic development level ($PGDP$), measured by the *per capita* income level of each country; 2) capital deepening (KL), measured by the ratio of capital stock and the number of employees in various industries of each country, to reflect the role of production mode in the GVC labor division. The larger the value of KL, the more capital-intensive the production mode will be; 3) exchange rate (ER), whose data provided by PWT.

To make the upgrading direction of four subsectors more in line with their own industry characteristics, this paper expands the research object from China to 62 countries and Rest of the World in this part. Panel data of four subsectors of equipment manufacturing industry from 2007 to 2019 are used for regression. For ease of calculation, all indexes are taken as logarithms. Hausman test results show that the fixed effect model (FE) is more suitable for Eq. 2, and the results are shown in Table 1.

The regression results show that for the four subsectors, the coefficients of upstream degree (U) in C12 and C15 are significantly positive, which indicates that the closer the embedded position of basic metals and metal products manufacturing subsector and transport equipment manufacturing subsector is to the upstream of the GVC, the more GVC upgrading can be realized; However, the coefficients of upstream degree (U) in C13 and C14 are not significant, which means that GVC upgrading of machinery equipment manufacturing subsector and electrical, electronic and optical equipment manufacturing subsector do not have an exact relationship with their embedded positions. Thus, basic metals and metal products manufacturing subsector (C12) and transport equipment manufacturing subsector (C15) can be classified as upstream leading sectors, and

10.3389/fenvs.2022.1044583

TABLE 1 Regression results of upstream degree and GVC upgrading in subsectors of equipment manufacturing industry.

	Eq. 2			
	C12	C13	C14	C15
lnU	1.372***(13.84)	0.051 (0.37)	−0.010 (−0.07)	1.406***(3.35)
lnPGDP	0.638***(9.35)	0.616***(5.68)	0.417***(3.30)	1.860***(4.57)
lnKL	−0.191***(−3.33)	−0.099 (−1.03)	−0.523***(−4.61)	−0.392 (−1.09)
lnER	0.155***(2.95)	−0.070 (−0.85)	0.093 (0.98)	−0.230**(−2.33)
R^2	0.398	0.086	0.031	0.035

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 2 Subsectors classification of equipment manufacturing industry.

Subsectors	ISIC Rev.3	GB/4757-2017	Classification
C12	Basic metals and metal products manufacturing industry	Metal products manufacturing industry	Upstream leading sectors
C13	Machinery equipment manufacturing industry	General equipment manufacturing industry	Mixed leading sectors
		Special equipment manufacturing industry	
C14	Electrical, electronic and optical equipment manufacturing industry	Electrical machinery and equipment manufacturing industry	Mixed leading sectors
		Computers, communications and other electronic equipment manufacturing industry	
		Instrument manufacturing industry	
C15	Transport equipment manufacturing industry	Automobile manufacturing industry	Upstream leading sectors
		Railway, ship, aerospace and other transport equipment manufacturing industry	

machinery equipment manufacturing subsector (C13) and electrical, electronic and optical equipment manufacturing subsector (C14) should be classified as mixed leading sectors, as shown in Table 2.

3.2 Econometric model design

This paper constructs an econometric model with green technology innovation (GTI) as the core explanatory variables as well as export technology complexity (TSI) as the explained variable to identify the impact of green technology innovation on GVC upgrading in China's equipment manufacturing industry and four subsectors, which is shown as follows.

$$TSI_{i,t} = \beta_0 + \beta_1 GTI_{i,t} + \beta_2 GTI_{i,t}^2 + \beta_3 CV_{i,t} + \varepsilon_{i,t} \tag{3}$$

where $CV_{i,t}$ stand for control variables, which mainly include: 1) ownership structure (SOW), measured by the proportion of employees in state-owned units in the average annual number of all employees in the industry; 2) foreign investment intensity (FOR), measured by the ratio of foreign capital in an industry to the total industrial output value; 3) industry concentration ($SIZE$), measured y the ratio between the total industrial output value and the enterprises number of the industry.

Based on the baseline regression, this paper also further analyzes the possible impact paths of green technology innovation on GVC upgrading referring to stepwise regression method (Baron and Kenny, 1986). Because of its effectiveness in testing the mediating effect, the stepwise regression method is widely used in the empirical research of various mechanism analysis (Luo and Xie, 2021; Wang and Li, 2022). The mediating effect test model in this paper is constructed as follows.

$$M_{i,t} = \gamma_0 + \gamma_1 GTI_{i,t} + \gamma_2 CV_{i,t} + \varepsilon_{i,t} \tag{4}$$

$$TSI_{i,t} = \delta_0 + \delta_1 GTI_{i,t} + \delta_2 M_{i,t} + \delta_3 GTI_{i,t}^2 + \delta_4 CV_{i,t} + \varepsilon_{i,t} \tag{5}$$

where $M_{i,t}$ stand for mediating variables, which mainly include: 1) pollution cost (PC), measured by the ratio of industrial pollution control cost to GDP; 2) embedded dependence (ED), measured by the ratio of technology introduction expenditure to the total industrial output value; 3) export scale (ET), measured by the ratio of export delivery value of each industry to GDP; 4) green product innovation ($GPTI$), measured by the sales revenue of new products per unit energy consumption; 5) green process innovation ($GPSI$), measured by the sum of the internal expenditure of R&D funds and the investment of technological transformation funds. In Eqs 3–5, if the regression results show that β_1, γ_1 and δ_2 are all significant in turn, the mediating effect exists, and the mediating variable is effective at this time. On this basis, if δ_1 is also significant, it indicates that both direct and indirect effects of green technology innovation on GVC upgrading exist; otherwise, only indirect effect exists.

3.3 Green technology innovation

Referring to the research of Yuan and Chen (2019), green technology innovation (GTI) in this paper is represented by the proportion of green technology innovation investment ($GREEN$) in the total industrial output value (X). And green technology innovation investment can be defined as the R&D investment caused by the government's environmental regulation based on the research of Hamamoto (2006). Actually, environmental regulation helps to guide enterprises more willing to accept cleaner production technologies, thus to increase R&D investment (Zhang et al., 2013). The relationship between environmental regulation and R&D investment can be expressed as:

$$\ln \boldsymbol{RD_{i,t}} = \boldsymbol{\alpha}_0 + \boldsymbol{\alpha}_1 \boldsymbol{ESR_{i,t-1}} + \boldsymbol{\alpha}_2 \boldsymbol{ESR^2_{i,t-1}} + \boldsymbol{\alpha}_3 \boldsymbol{SCALE_{i,t-1}} + \boldsymbol{\alpha}_4 \boldsymbol{SCA_{i,t-1}} + \boldsymbol{\alpha}_5 \boldsymbol{FDI_{i,t-1}} + \boldsymbol{\varepsilon_{i,t}} \tag{6}$$

where the subscripts i and t stand for sector and year, respectively. $RD_{i,t}$ denotes the R&D investment in year t for sector i, which is measured by the total expenditure of R&D investment of each sector and take logarithms in the empirical process to increase stability; $ESR_{i,t-1}$ denotes the environmental regulation intensity in one lag periods of year t for sector i. In consideration of the availability and integrity of data, and to avoid the error caused by the difference of industrial structure, this paper revises the index set by Levinson (1996) to be expressed as $ESR_{i,t} = ESR^*_{i,t}/R_{i,t}$. Future more, $ESR^*_{i,t}$ is equal to $P_{i,t}/X_{i,t}$, where $P_{i,t}$ and $X_{i,t}$ indicate industrial pollution control investment and total industrial output value in year t for sector i, respectively; and $R_{i,t}$ is equal to $X_{i,t}/GDP_t$, where GDP_t indicates gross national product of the whole country in year t. The smaller the value of $ESR_{i,t}$, the weaker the environmental regulation intensity in year t for sector i, and $ESR^2_{i,t-1}$ is used to reveal the possible non-linear relationship between environmental regulation intensity and R&D investment. Control variables mainly include industrial scale ($SCALE$), which is measured by the proportion of the total industrial output value to GDP; fixed assets scale (SCA), which is measured by the proportion of the net industrial fixed assets to GDP; foreign direct investment (FDI), which is measured by the proportion of the industrial foreign capital to GDP. $\varepsilon_{i,t}$ represents the random error term. All explanatory variables are set to lag one periods, due to the delay of environmental regulation on R&D investment. And in order to avoid possible endogeneity problem, SYS-GMM is introduced to conduct regression analysis on the empirical data of China's equipment manufacturing industry from 2007 to 2019 for its widely use to solve the problem of weak instrumental variables. The results are shown in Table 3.

It can be seen that AR 1) test is significant while AR 2) test is not, that is, there is no second-order autocorrelation in the model, indicating that the SYS-GMM method is reasonable. At the same time, the general moment condition of the model holds, that is, the selection of instrumental variables is also effective according to the results of Hansen test and Sargan test. The coefficient of ESR and ESR^2 are significantly negative and positive at the significance level of 5% respectively, indicating that with the increase of environmental regulation, R&D investment decreases first and increases subsequently. The reason for this trend is that enterprises lack the consciousness of green technology innovation in the early stage of the implementation of environmental regulation. As a result, the R&D investment are crowed out by the cost of pollution control, resulting in a negative correlation between environmental regulation and R&D investment. With the continuous improvement of the intensity of environmental regulation, enterprises need to cost more to control environmental pollution. At this time, environmental regulation can force enterprises to vigorously develop green technology to reduce pollution emission and improve competitiveness. Therefore, there is a positive correlation between environmental regulation and R&D investment in the later stage.

Overall, the relationship between environmental regulation and R&D investment shows U-shaped according to the coefficients' direction of $ESR_{i,t-1}$ and $ESR^2_{i,t-1}$. Based on this conclusion, green technology innovation investment ($GREEN$) can be measured as:

$$\boldsymbol{GREEN_{i,t}} = (\boldsymbol{\alpha}_1 + 2\boldsymbol{\alpha}_2 \boldsymbol{ESR_{it-1}}) \times \boldsymbol{RD_{i,t}} \times \Delta \boldsymbol{ESR_{i,(t,t-1)}} \tag{7}$$

where the value of α_1 and α_2 are equal to the coefficients of $ESR_{i,t-1}$ and $ESR^2_{i,t-1}$ given in Table 3, respectively. According to the analysis of Hamamoto (2006), the investment in green technology innovation will have a crowding out effect on the resources actually produced. Since the former is necessarily greater than the latter, the value of $GREEN$ calculated as negative is set to 0. Finally, the green technology innovation (GTI) of China's equipment manufacturing industry can be calculated.

TABLE 3 Regression results of environmental regulation and R&D investment in China's equipment manufacturing industry.

	Eq. 6
ERS	−5.579**(−4.11)
ERS^2	1.734**(3.58)
$SCALE$	−32.970**(−4.62)
SCA	94.332**(2.57)
FDI	−215.647*(−3.31)
RD_{t-1}	3.455*(3.24)
AR (1)	−1.33 (0.23)
AR (2)	−0.32 (0.67)
Hansen	0.00 (1.000)
Sargan	52.77 (0.000)

t-value is shown in parentheses for the first five variables, and *p*-value is shown in parentheses for the last four tests; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

3.4 Global value chain upgrading

Referring to the research of Wang and Wei (2017), this paper takes the index of export technology complexity (TSI) to measure the level of GVC upgrading, which is improved based on the calculation method of Hausman et al. (2005). Export technology complexity is weighted average of GDP *per capita* of each country in the world with the weight of the index of revealed comparative advantage (RCA), and then reflects the value acquisition ability of a country in the GVC. However, with the continuous development of value- added accounting methods, there may be some deviations in calculating the index of export technology complexity by gross statistical caliber. Therefore, in this paper, the index of export technology complexity is revised to value-added technology complexity, with the calculation formula as follows.

$$\boldsymbol{TSI_{i,j}} = \boldsymbol{RCA_{i,j}} \times \boldsymbol{I_j} = \frac{\boldsymbol{VAX_{i,j}} / \boldsymbol{VAX_j}}{\sum_j \boldsymbol{VAX_{i,j}} / \sum_j \boldsymbol{VAX_j}} \times \boldsymbol{I_j} \tag{8}$$

where the subscripts i and j stand for sector and country, respectively. I_j denotes the GDP *per capita* for country j; VAX_j denotes the value-added contained in the gross export from country j, whose calculation method refers to Koopman et al. (2010) and can be shown as:

$$\boldsymbol{VAX_j} = \sum_{s} (\boldsymbol{V_j B_{js}} \sum_{t \neq j} \boldsymbol{Y_{st}}) \tag{9}$$

where s, j and t stand for countries with trade contacts. V_j denotes a $1 \times N$-dimensional row vector of value-added in country j who has N industrial sectors; B_{js} denotes a $N \times N$-dimensional Leontief inverse matrix, indicating that country s increases by per unit of final demand required to input j produced; Y_{st} denotes a $N \times 1$-dimensional column vector, indicating the final demand in country t provided by country s.

3.5 Data sources

The indexes identified above and those to be used in the future mainly come from three kinds of database: 1) the UIBE (University of International Business and Economics) GVC Indicators database, which is a derivative database processed based on different kinds of original world ICIO (Intercountry Input-output Tables) table. The world ICIO table used in this paper provided by ADB (Asian Development Bank). 2) the statistical yearbooks provided by China National Bureau of Statistics, included China Statistical Yearbook, China Statistical Yearbook on Science and Technology, China Statistical Yearbook on Industry and China Statistical Yearbook on Environment. 3) official websites of international organizations, included the World Bank, OECD (Organization for Economic Co-operation and Development), PWT (Penn World Table). One problem to be solved is that the division of equipment manufacturing industry in these three kinds of databases are inconsistent. In the ICIO provided by ADB, the industry classification follows the International Standard Industry Classification (ISIC Rev.3), while in the statistical yearbooks provided by China, it follows the National Economic Standard Industry Classification (GB/4757-2017). In order to facilitate the research, this paper classifies the industries divided by GB/4757-2017 according to ISIC Rev.3, and obtains four subsectors of equipment manufacturing industry. For details, please refer to Table 2.

TABLE 4 Regression results of green technology innovation and GVC upgrading in subsectors of equipment manufacturing industry.

	Eq. 3		
	The full sample	Upstream leading sectors	Mixed leading sectors
GTI	−1.992*** (−3.34)	−3.381***(−5.05)	0.794***(8.16)
GTI^2	1.015**(2.35)	1.919***(3.84)	−0.589***(−9.31)
SOW	−2.322***(−4.21)	−0.905*(−1.83)	−5.592***(−29.51)
FOR	−5.612 (−1.61)	−7.441**(−2.50)	−9.861***(−7.92)
SIZE	−0.266***(−4.21)	−0.011 (−0.10)	0.123***(6.57)
Con_s	10.509***(40.63)	10.132***(37.83)	9.861***(113.85)
R^2	0.906	0.889	0.995

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4 Empirical results

4.1 Baseline regression

For Eq. 3, the benchmark regression results are shown in Table 4 together with the subsector heterogeneity analysis using Weighted Least Squares (WLS) regression method. It can be seen that for the full sample, the coefficient of GTI is significantly negative, and that of GTI^2 is significantly positive, indicating that there is a U-shaped relationship between green technology innovation and GVC upgrading, which decreases first and increases subsequently. That is to say, for China's equipment manufacturing industry, green technology innovation is not conducive to the advancement of the GVC labor division in the early stage, but in the long run, with the ability of green technology innovation gradually enhanced, the GVC position will be improved after crossing an inflection point. In the early stage of green technology innovation, enterprises need to bear high R&D and design costs and huge risk, which forms the "crowding out" of normal production activities and non-green technological innovation. Since other developed countries have advanced green technologies, it is difficult for China's equipment manufacturing industry to imitate and absorb the key links. At the same time, these green technologies will form certain trade barriers to China, further restricting GVC upgrading. In addition, when the benefit brought by green technology innovation is far less than the cost of innovation and pollution control, the production efficiency of enterprises will continue to decline, inhibiting their enthusiasm to participate in GVC. However, with the continuous enhancement of green technology innovation ability, enterprises can absorb and transform foreign cutting-edge green technologies and form a mature green innovation system. This can not only help Chinese enterprises reduce production costs and improve efficiency, but also greatly reduce environmental pollution, which can break the green trade barriers from developed countries, and make enterprises gain more value-added, thereby promoting the GVC upgrading of the whole industry.

After analyzing the regression results of the full sample, this paper also discusses the heterogeneity of the two groups of equipment manufacturing subsectors. The results show that the relationship between green technology innovation and GVC upgrading for upstream leading sectors is similar to that of the full sample, with a U-shaped trend of declining first and rising subsequently. While for mixed leading sectors, there is an inverted U-shaped relationship between green technology innovation and GVC upgrading, indicating that green technology innovation can promote GVC upgrading in the short term, but in the long run, it is the opposite. This is because the GVC upgrading direction of the mixed leading sectors is not unique, and must be determined according to its value-added capacity in different GVC stages as well as its production conditions. The inverted U-shaped regression results indicate that at the present stage, green technology innovation in China's machinery equipment manufacturing industry and electrical, electronic and optical equipment manufacturing subsector is not completely suitable for their GVC upgrading. Therefore, it is necessary to continue to explore more scientific and effective approaches of green technology innovation according to the characteristics of the industry.

As for the control variables, the ownership structure (*SOW*) has a significant inhibitory effect on GVC upgrading, indicating that the increase in the proportion of state-owned units is not conducive to improving the value acquisition ability of the industry in the GVC, and the role of the market should be given more play. The foreign investment intensity (*FOR*) has an insignificant inhibitory effect on GVC upgrading. Although foreign investment can introduce a large number of advanced green technologies from developed countries, it is often accompanied by industrial relocation. That is, developed countries are more inclined to transfer production links with high pollution and low value-added to countries with imperfect

TABLE 5 Robustness regression results of green technology innovation and GVC upgrading.

	Robustness regression of Eq. 3		
	a)	b)	c)
GTI	−1.992*** (−3.34)	−1.320***(−3.14)	
GTI^2	1.015**(2.35)	0.539*(1.75)	
GTI_{t-1}			−2.064***(−3.39)
${GTI_{t-1}}^2$			1.240***(2.77)
SOW	−2.322***(−4.21)	−1.181***(−2.98)	−2.017***(−4.25)
FOR	−5.612 (−1.61)	−12.668***(−4.98)	−2.113 (−0.55)
$SIZE$	−0.266***(−4.21)	−0.407***(−8.60)	−0.150**(−2.50)
K		0.000***(7.11)	
Con_s	10.509***(40.63)	9.922***(51.60)	10.181***(35.08)
R^2	0.906	0.949	0.840

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

environmental regulations and standards, resulting in the "pollution paradise" effect. The governments receiving the transfer is usually willing to lower environmental standards or relax relevant regulations, resulting in a vicious circle of low-end lock-in. In addition, foreign investment mainly flows to the low-technology or labor-intensive sectors of equipment manufacturing industry, while most of core green technologies are kept in the home country without spillover, which cannot promote the GVC upgrading for the recipient country. The Industry concentration ($SIZE$) has a significant inhibitory effect on GVC upgrading with sector heterogeneity. This is because China's equipment manufacturing industry is mainly engaged in the production of low value-added links, and the increase of industry concentration will intensify the "low-end lock-in".

4.2 Robustness regression

In order to ensure the robustness of baseline regression results, this paper regresses Eq. 3 in three ways: a) in order to avoid the extreme values in the data calculation, the special samples that may affect the regression results are eliminated, and the export technology complexity (TSI) and green technology innovation (GTI) are processed with bilateral tail reduction at 1% quantile; b) adding control variables. The flow and share of production factors such as capital and labor can reflect the production capacity, which is important on affecting GVC upgrading. Therefore, capital intensity (K) is considered as an omitted variable in the robustness test part, measured by the ratio of the net fixed assets to the number of employees in the industry; c) replace the core explanatory variable as one-period lag phase of green technology innovation ($GTI_{i,t-1}$). As shown in Table 5, the regression results are still robust, indicating that the baseline empirical conclusions are scientific.

Next, this paper further tests the robustness of the sectoral heterogeneity analysis, by setting the index of GVC control capability (GVC_DOM) to measure GVC upgrading instead of export technology complexity (TSI). The index of GVC control capability is calculated as follows.

$$\boldsymbol{GVC\_DOM_j} = \frac{\boldsymbol{FVA\_INT_j}}{\boldsymbol{VS_j}} = \sum_{s\neq j}\sum_{t\neq j}\frac{\boldsymbol{V_s B_{sj} A_{jt}(1-A_{tt})^{-1} Y_{tt}}}{\boldsymbol{V_s B_{sj}\widehat{E}_j + V_t B_{tj}\widehat{E}_j}} \tag{10}$$

where A_{jt} denotes a $N \times N$-dimensional matrix, indicating that country t increases by per unit of direct demand required to input j produced; E_j is a $N \times 1$ vector giving gross exports of country j, and $\widehat{E}_j$ denotes a diagonal matrix with the export vector E_j in its diagonal. VS_j stands for the foreign value-added in exports of country j, and FVA_INT_j is part of VS_j, that is the foreign value-added contained in the exports of intermediate products. The higher the proportion of FVA_INT_j to VS_j is, the closer the main way for country j to obtain value-added from GVC is to the middle-end and high-end value-added links. With the new explained variable, first of all, it is necessary to verify that the group division for subsectors of the equipment manufacturing industry is stable. Thus, Eq. 9 can be reset as Eq. 11, whose robustness regression results are shown in Table 6.

$$\boldsymbol{GVC\_DOM_{i,t}} = \boldsymbol{\gamma_0 + \gamma_1 U_{i,t} + \gamma_2 CV_{i,t} + \varepsilon_{i,t}} \tag{11}$$

The result is same as before. That is, the upstream leading sectors include basic metals and metal products manufacturing subsector (C12) and transport equipment manufacturing

TABLE 6 Robustness regression results of upstream degree and GVC upgrading in subsectors of equipment manufacturing industry.

	Eq. 11			
	C12	C13	C14	C15
lnU	0.168*(1.71)	0.100 (1.23)	0.043 (1.21)	0.252***(3.43)
lnPGDP	−0.153**(−2.26)	−0.155**(−2.40)	−0.056*(−1.72)	−0.176**(−2.22)
lnKL	0.109*(1.90)	0.129**(2.27)	0.128***(4.36)	0.180***(2.72)
lnER	−0.045 (−0.86)	−0.055 (−1.11)	−0.043*(−1.74)	−0.002 (−0.03)
R^2	0.015	0.016	0.038	0.027

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 7 Robustness regression results of green technology innovation and GVC upgrading in subsectors of equipment manufacturing industry.

	Eq. 12		
	The full sample	Upstream leading sectors	Mixed leading sectors
GTI	−0.282**(−2.12)	−0.501**(−2.60)	0.249***(8.34)
GTI^2	0.187**(2.27)	0.344**(2.84)	−0.170***(−8.69)
SOW	0.107 (0.84)	0.760***(5.51)	−0.692***(−17.26)
FOR	−2.206***(−3.36)	−5.790***(−10.77)	−1.815***(−4.63)
SIZE	−0.014 (−1.01)	−0.071***(−5.99)	−0.006 (−0.97)
Con_s	0.510***(8.29)	0.642***(10.03)	0.450***(21.03)
R^2	0.998	0.995	0.995

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

subsector (C15), and the mixed leading sectors include machinery equipment manufacturing subsector (C13) and electrical, electronic and optical equipment manufacturing subsector (C14). Subsequently, the explained variable of Eq. 5 is also be replaced to verify the robustness of the sectoral heterogeneity analysis. The new regression equation is shown as Eq. 12, whose regression results are represented in Table 7. According to the results, the empirical conclusions are found to be robust.

$$\boldsymbol{GVC\_DOM_{i,t} = \mu_0 + \mu_1 GTI_{i,t} + \mu_2 GTI_{i,t}^2 + \mu_3 CV_{i,t} + \varepsilon_{i,t}} \quad (12)$$

4.3 Further analysis of impact paths

On the basis of the significant coefficients of the core explanatory variables in the benchmark regression results, it is feasible to further test if the mediating effect of green technology innovation on GVC upgrading for China's equipment manufacturing industry exists through Eqs 6, 7. The test results of all five mediating variables, including pollution cost (*PC*), embedded dependence (*ED*), export scale (*ET*), green product innovation (*GPTI*) and green process innovation (*GPSI*), are shown in Table 8 and Table 9.

For pollution cost (*PC*), it can be seen that in Table 8 that the effect of green technology innovation on environmental pollution cost is obviously inhibited, indicating that green technology innovation can actively reduce the cost of environmental pollution in the production process. But in Table 9, there is a positive relationship between the pollution cost and the promotion of GVC upgrading, which indicates that the high cost of pollution actually promotes the improvement of value-added capacity. This is because at this stage, China is still suffering from the diversion of pollution emissions from developed countries. The model of embedding GVC through the export of polluting, energy-intensive, low value-added products is not completely over. Despite the pollution, economies of scale can bring market advantages. Thus, it is still conducive to China's equipment manufacturing industry in the GVC to improve the international labor division and increase the value-added, which will further increase the energy consumption of industrial production. In addition, although

TABLE 8 Test results of impact paths.

	Eq. 4				
	PC	*ED*	*ET*	*GPTI*	*GPSI*
GTI	−0.463*** (−4.81)	−0.008*** (−7.29)	0.657*** (2.78)	0.121*** (4.28)	0.857*** (3.86)
SOW	−1.406*** (−3.46)	0.067*** (3.89)	−1.718** (−2.22)	0.199 (0.76)	−0.923 (−1.51)
FOR	3.454 (1.32)	0.377*** (3.54)	10.734** (2.26)	1.451 (0.77)	17.870*** (4.86)
SIZE	0.170*** (3.52)	−0.010*** (−5.67)	0.356*** (3.35)	0.209*** (8.02)	0.567*** (6.09)
Con_s	−0.866*** (−6.58)	0.001 (0.74)	−5.308*** (−16.32)	−0.241*** (−4.92)	14.035*** (48.04)
R^2	0.652	0.999	0.224	0.995	0.535

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 9 Test results of impact paths (continue).

	Eq. 5				
	PC	*ED*	*ET*	*GPTI*	*GPSI*
GTI	−2.029*** (−3.54)	−2.127*** (−4.87)	−2.049*** (−3.55)	−3.040*** (−8.10)	−1.958*** (-3.99)
GTI^2	1.164*** (2.77)	1.016*** (3.13)	0.986** (2.33)	1.680*** (4.89)	0.705* (1.86)
PC	0.360** (2.19)				
ED		−32.626*** (−6.04)			
ET			0.149* (1.80)		
GPTI				0.637** (2.53)	
GPSI					0.341*** (4.33)
SOW	−1.714*** (-2.87)	−1.419*** (−3.46)	−2.046*** (−3.77)	−0.524*** (−3.08)	−1.668*** (−3.78)
FOR	−7.471** (-2.16)	−4.312* (−1.73)	−6.951** (−2.02)	−8.803*** (−4.95)	−10.837*** (−3.60)
SIZE	−0.338*** (-4.89)	−0.341*** (−7.16)	−0.291*** (−4.65)	−0.110 (−1.46)	−0.368*** (−6.46)
Con_s	10.893*** (35.82)	10.983*** (54.04)	11.232*** (23.63)	9.973*** (42.86)	5.427*** (4.59)
R^2	0.915	0.936	0.906	0.952	0.911

t-value is shown in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively.

green technology innovation can reduce the cost of environmental pollution, enterprises have to bear the additional cost of environmental pollution treatment in the short term, which increases the total production cost and becomes an inhibiting factor for GVC upgrading. In the long run, the existing development mode of China's equipment manufacturing industry will deepen its technological dependence on GVC and lock the low-end, which is not conducive to the long-term development. While enterprises that actively carry out green technology innovation will significantly reduce the cost of environmental pollution treatment, and even can reach zero cost due to a major breakthrough in green technology. Therefore, China needs to actively promote green technology innovation to improve energy efficiency, increase the transfer of low-end and high-energy consumption industries, and reshape the pattern of GVC. To sum up, green technology innovation can reduce the cost of environmental pollution treatment, but it will inhibit the GVC upgrading in the short term.

For embedded dependence (*ED*), it can be seen in Table 8 that green technology innovation can effectively reduce the embedded dependence on GVC, with obvious inhibitory effects between the two. Meanwhile, in the process of GVC upgrading of China's equipment manufacturing industry, there is still an obvious inhibitory effect between embedment dependence and GVC upgrading, as shown in Table 9. These indicates that for a long time, China's position at low-end of GVC dominated by developed countries has prevented it from upgrading and increasing value-added in the international labor division. On the whole, green technology innovation can effectively reduce the embedded dependence on GVC, so as to promote the transformation and upgrading of China's equipment manufacturing industry.

For export scale (*ET*), it can be seen that in Table 8 that green technology innovation can effectively promote export scale, indicating that green technology innovation can optimize export trade structure and enhance competitiveness. Table 9 shows that the impact of export scale on GVC upgrading is also significantly positive, indicating that the expansion of export scale promotes the improvement of the embedding position of GVC and can increase value-added gained from export. Therefore, in the GVC upgrading process of China's equipment manufacturing industry, green technology innovation can effectively promote the further promotion of the international labor division status by optimizing the export trade structure and increasing exports.

For green product innovation (*GPTI*) and green process innovation (*GPSI*), it can be seen in Table 8 that the influence of green technology innovation on green product innovation and green process innovation are all significantly positive. Green technology innovation is helpful to strengthen energy saving and emission reduction in all stages of product life cycle, and is also beneficial to realize product transformation or R&D design in the production process, and provide more green products and processes in line with environmental protection requirements. In Table 9, the regression coefficient of green product innovation and green process innovation are both obviously positive, indicating that these two mediating indexes can help China's equipment manufacturing industry realize GVC upgrading. In general, green technology innovation can promote the innovation of green products and green processes, so as to further strengthen its comparative advantages, and improve the position in GVC labor division and increase the industrial value- added.

5 Conclusion and policy implications

On the basis of existing research, this paper firstly defines the GVC upgrading direction for subsectors of equipment manufacturing industry using the ICIO provided by ADB database of 63 countries from 2007 to 2019. According to the effect of upstream degree index on GVC upgrading, the four subsectors of equipment manufacturing industry are classified as upstream leading sectors and mixed leading sectors respectively. Subsequently, the benchmark regression results of full samples and heterogeneity analysis in China's manufacturing industry are discussed to study the relationship between green technology innovation and GVC upgrading. Furthermore, stepwise regression method and five mediating variables are introduced to verify the impact approaches of green technology innovation on GVC upgrading. In the whole process, the robustness test is carried out by replacing core explanatory variables. The regression results show that, 1) from the overall perspective of China's equipment manufacturing industry, there is a U-shaped relationship between green technology innovation and the promotion of GVC status. That is, green technology innovation can play a positive role in promoting the GVC upgrading only after crossing an inflection point. Therefore, it is very important to create a good innovation environment and atmosphere and coordinate relevant policy about green technology innovation and development, which can help the industry to realize the transition from "demographic dividend" to "talent dividend". At the same time, the establishment and improvement of the intellectual property protection system can strengthen the protection of enterprises' green technology, which can actively encourage enterprises to carry out green technology innovation, reduce the GVC embedded dependence and optimize the export trade structure, and finally, promote the upgrading of the GVC status. 2) from the perspective of industry heterogeneity, for upstream leading sectors including basic metals and metal products manufacturing subsector and transport equipment manufacturing subsector, green technology innovation and GVC upgrading have a U-shaped relationship of first decline and then rise; but for mixed leading sectors including machinery equipment manufacturing subsector and electrical, electronic and optical equipment manufacturing subsector, the trend is opposite, that is, an inverted U-shaped relationship of first rise and then decline. This indicates that heterogeneity of China's equipment manufacturing industry would need to get more attention, including fully stimulating the guide role of the market and the advantages of various types of environmental regulation tools. By improving the government's environmental supervision system, enterprises are forced to reduce pollution costs and carry out green product and green process innovation, so as to enhance the value-added capacity when embedded in GVC. 3) from the perspective of impact paths, green technology innovation in China's equipment manufacturing industry can promote GVC upgrading by reducing its dependence on GVC, optimizing export trade, reducing pollution costs, and promoting green product and process innovation. Therefore, the establishment and improvement of factor market supply system can provide green financial support and cultivate green innovative talents for China's equipment manufacturing enterprises to carry out green technology innovation, and find a breakthrough for promoting the improvement of GVC labor division. According to the above conclusions, this paper puts forward the following three policy implications.

First, improve the government's environmental regulation policy, and force enterprises to carry out green technology innovation. It is very important to make full use of and coordinate the advantages of different government regulation means and market mechanisms. According to the actual situation of China's equipment manufacturing industry, appropriate policy mix should be made to drive enterprises to carry out green technology innovation through environmental regulation pressure and pollution control cost, so as to help the industry breakthrough the "low-end lock-in" and promote GVC upgrading. The government should strengthen the innovation of environmental regulation policies, and speed up the improvement and implementation of environmental tax, carbon tax and emission quota. By improving the supervision and implementation effect of environmental laws and regulations, the environmental protection needs of China's economy and China's equipment manufacturing industry for sustainable development can be met, and the coordination of green economic and ecological environmental protection can be promoted. At the same time, it is worth noting that the unlimited increase of environmental regulation will increase the crowding out of "compliance cost" to "compensation cost", which can increase the total cost of enterprises, and then affect the development of green technology innovation as well as hinder the advancement of GVC status. In addition, environmental regulation policies should consider the industry characteristics and upgrading direction of China's equipment manufacturing enterprises, and encourage enterprises to upgrade towards the leading link of GVC. On the one hand, for equipment manufacturing industry in upstream leading group, it is necessary to promote the upgrade of the industry to the GVC upstream by encouraging enterprises to carry out green technology innovation and training green innovation talents, so as to form a comparative advantage in R&D and design instead of population and resource endowment. On the other hand, for equipment manufacturing industry in mixed leading group, their labor division links that can generate higher value-added are not unique and have a trend of industrial integration. GVC upgrading plan should be formulated according to the characteristics of the industry, and the development pattern of a certain industry should not be completely copied.

Second, improve the market supply system for factors of production and strengthen the training of green and innovative personnel. The government should formulate scientific and reasonable financial and fiscal policies, increase financing channels and financial supply, increase investment in green technology innovation in the equipment manufacturing industry, and encourage enterprises to initiate green technology innovation. The government also should reduce the cost of green technology innovation for equipment manufacturing enterprises, including improving targeted subsidies, tax rebates and other policies, encourage enterprises to carry out green process and green product innovation and mobilize their enthusiasm. Financial institutions should actively cooperate with equipment manufacturing enterprises to lower the financing threshold and reduce the cost of green innovation. In order to change from "demographic dividend" to "talent dividend", it is necessary to strengthen the investment in human capital, improve the personnel training policy, and increase the cultivation and training of green and innovative talents. At the same time, it is also necessary to improve the mode of production, education and research, strengthen the cooperation between universities, research institutes and enterprises, so as to better adapt to the market demand and the actual needs. On the one hand, the government should improve the talent introduction plan, actively introduce green and innovative talents, and attract well-known scholars and relevant talents at home and abroad to participate in the green technology research of the equipment manufacturing industry. On the other hand, the enterprise should cultivate the green innovation consciousness of employees in the enterprise, stimulate the green innovation spirit, and form a benign interaction between domestic and foreign talents.

Third, promote the green innovation-driven development strategy, shift from "factor driven" to "green innovation-driven". To improve the GVC labor division status of China's equipment manufacturing industry, the government must establish perfect market trading system and trading rules, guide and encourage enterprises to actively carry out green technology innovation, and implement relevant support measures for those enterprises to avoid research and development risks. The government should also supervise and restrict non-environmental innovation activities that may adversely affect the quality of the natural, ecological and environmental environment, eliminate enterprises with low technological level and great environmental damage, and reduce excess production capacity. China's equipment manufacturing enterprises need to actively invest in master core and key technologies to realize independent, controllable and modern development of the industry. In terms of environmental regulation, the government should strengthen the construction of relevant laws and regulations, improve the environmental supervision system, strengthen the supervision of waste water, soil, exhaust gas and other waste discharge of enterprises, and standardize and guarantee the implementation of environmental protection policies. Big data, satellite remote sensing and other technologies can be used to monitor the pollution situation of various industries in real time and promote the improvement of the pollution control level of the whole industry. When granting patents, industry associations should also pay attention to the environmental and energy effects. Patent classification, setting and dynamic regulation can lay a solid foundation for the implementation of green technology innovation incentive mechanism. At the same time, enterprises should promote the innovation of green products and processes, and the continuous improvement of product production accuracy and product quality, and the emergence of new products and new processes, so as to form the industry scale and produce the industrial cluster effect, and increase export trade to drive the industrial upgrading.

To sum up, this paper takes China's equipment manufacturing industry and four subsectors as the research object to verify the non-linear relationship between green technology innovation and GVC upgrading. The results show that the impact of green technology innovation on GVC upgrading is first decline and then rise, which is consistent with the research conclusions of Song et al. (2018) and Wang S. et al. (2021). On this basis, this paper also verifies the heterogeneity of the above non-linear relationship in different subsectors, which can provide targeted development reference for two types of equipment manufacturing subsectors with different upgrading directions of GVC. This is one of the important application contributions of this study. Moreover, this paper further explores the mediating mechanism of green technology innovation affecting the GVC upgrading, and find that pollution cost, embedded dependence, export scale, green product innovation and green process innovation play important roles in it. This can help China's equipment manufacturing industry to select targeted forms and paths of green technology innovation when participating in the world division of labor, encourage enterprises to carry out green technology innovation, and further promote the GVC upgrading.

This study provides a theoretical basis and policy reference for China to promote green technology innovation and realize GVC upgrading in equipment manufacturing enterprises. Nonetheless, this study has the following limitations. First, because of the data limitations, the time span chosen in this study to examine the impact of green technology innovation on GVC upgrading is from 2007 to 2019, and the latest value chain division of labor cannot be analyzed. Second, the enterprise is the main element of green technology innovation, shouldering the important task of improving the level of green R&D in the industry. However, due to the restriction of ADB database, this paper only conducts research through industry panel data, without exploring typical cases or conducting research. In future research, we will seek breakthroughs in these aspects.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: http://rigvc.uibe.edu.cn/english/D_E/database_database/index.

Author contributions

YL: conceptualization, methodology; HY: data processing, and writing (original draft); XZ: data collection, validation, and writing (review and editing); QH: visualization, investigation, supervision, and 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.

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