How does green technology innovation affect urbanization?  
An empirical study from provinces of China

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RESEARCH ARTICLE

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Abstract

The construction of new-type urbanization with the theme of innovation, green, and smart development is becoming the endogenous driving force of China’s economic transformation and upgrading, and green technological innovation is a key factor in cracking the problems of development motivation and environmental constraints in urbanization construction. This paper investigates the impact of green technology innovation on urbanization based on a panel dataset covering 30 provinces in China from 2005 to 2019. First, we use the entropy method and the super-efficiency DEA method to measure the level of urbanization and green technology innovation, respectively. Moreover, on this basis, we use panel regression model and FGLS model to estimate the direct impact of green technological innovation on urbanization and its three dimensions—population urbanization, industrial urbanization, and ecological urbanization. Then, the mediating effect model is used to further study the indirect impact of green technological innovation on urbanization. The results indicate that green technological innovation is the most effective way to promote the development of new urbanization currently. In addition, green technology innovation can indirectly affect urbanization through the effects of foreign capital, energy consumption and information development, while the effect of industrial structure optimization effects is not significant. Finally, some policy suggestions are discussed to better promote the development of urbanization in China.

Keywords
Green technology innovation · Urbanization · Impact mechanism · Mediating effect · Feasible generalized least squares · China

Introduction

Urbanization is an important driving force for economic growth and industrialization (Moomaw and Shatter, 1996; Yang et al., 2017). According to the data from the United Nations (2018), by 2050, 68% of the world’s population will live in cities. As the largest developing country of the world, China’s urbanization process has entered a stage of rapid development since the late 1970s. Relevant data show that China’s urban permanent population ratio has increased from 17.9% in 1978 to 63.89% in 2020, which means that historic achievements have been made in urban construction. Yet, China currently appears almost all the expected consequences of rapid urbanization, such as uneven regional development, excessive land consumption, and environmental pollution (Liang et al., 2019; Kuang et al., 2020). The report of the 19th National Congress of the Communist Party of China has pointed out that high-quality urbanization is becoming a new requirement and trend for China’s future economic development. In other words, it should be the focus of urbanization that from aspects of industrial support, living environment and social security to realize the transformation from rural to urban, in order to maintain the coordinated development of economy, society and environment, not just urban expansion (Li, 2012) and the increase in the proportion of the population. However, obviously, the inertia of the extensive model of China’s urbanization development is still very large, and the hard constraints of the path-locking effect are difficult to change in a short period of time.

Facing the dilemma that the rapid development of urbanization at the expense of environment damage, green technology
innovation, which is characterized by sustainability and innovation, is emerging as an ideal solution to address the thorny problems (Wan and Huang 2004). Green technology innovation can lead to the sustainable development of environment through product innovation (Oltra and Saint 2009), thus bring remarkable environmental benefits, not just easing environmental burden (Driessen et al. 2013). Current studies have discussed the relationship between the two from the national and regional levels, such as direct relationship and indirect relationship (Chen and Ding 2015; Xu et al. 2020), but there are few studies that have made an in-depth exploration of the influence mechanism between them. In addition, the impact of green technology innovation on urbanization is a comprehensive and complex process, and different types of urbanization are affected by green technology innovations differently. Therefore, it is necessary to subdivide the types of urbanization for further discussion.

The main contributions and innovations of this paper are as follows: first, based on the panel data of 30 provinces in China from 2005 to 2019, we try to supplement the previous research by analyzing the direct and indirect effects of green technological innovation on urbanization. Second, we subdivide urbanization into population urbanization, industrial urbanization and ecological urbanization, and further investigate the impact of green technological innovation on different types of urbanization in order to make more targeted policy recommendations. In addition, in the discussion of the indirect impact of green technological innovation on urbanization, we have conducted research through industrial structure effects, foreign investment effects, energy consumption effects, and information development effects, which perspective is further than previous studies. This study is predicted to provide deeper insights for policy makers in terms of the impact of green technological innovation on urbanization and can be conducive to the realization of the goal of new-type urbanization.

The remainder of this paper is organized as follows. The “Literature review” section provides the literature review. The “The impact mechanism of green technological innovation on urbanization” section introduces the mechanism of green technology innovation affecting urbanization. The “Methodologies” section describes the methods, variables and data sources. The “Results and discussions” section shows the results and discussions of the empirical analysis. The “Conclusions and policy implications” section proposes the conclusions and policy implications.

**Literature review**

Characterized by floating population and urban land expansion (Luo et al. 2018), urbanization is the trend of demographic and economic transformation in developing countries, particularly in Asia and Africa (Montgomery 2008). Krey et al. (2012) pointed out that the process of urbanization has shown to be very important for economic development, especially in developing countries. According to the study of Song et al. (2018), urbanization had become a vital engine of economic growth. Rapid urbanization, however, may be developed at the expense of economy and environmental problems. While China’s urbanization is developing at an unprecedented speed, various risks and problems have also emerged, such as environmental sustainability issues (Liu et al., 2019; Ahmed et al. 2020b; Ariken et al. 2021), excessive CO₂ emissions problems (Huo et al., 2020, 2021), excessive soil erosion and land consumption (Jeong and Dorn 2018; Kuang et al., 2020), rural land degradation (Li et al., 2018), and urban–rural inequality (Guo et al. People, 2018). Meanwhile, the rapid growth of urban population had put tremendous pressure on environmental security, because it may not only reduce the per capita access to survival resources but also reduce the total supply of certain resources (Buhaug and Urdal, 2013). Besides, with the widening of the urban–rural gap, the rapid urbanization process has brought threats to the lives and well-being of urban and rural residents (Yuan et al., 2018; Ahmed et al., 2020a).

How to solve a series of production and life problems brought about by urbanization requires researching from the factors affecting urbanization. As an important driving force of urbanization, technological innovation plays a key role in promoting the development of urbanization (Liu and Dong, 2021). Bettencourt et al. (2007) proposed that it was necessary for the implementation of urban sustainable development to shorten the cycle of technology innovation. Qiu (2013) proved that urbanization promoted technological innovation by collecting production factors, inducing effective demand and accelerating spatial diffusion. Wu et al. (2013) found that the development of urbanization would re-allocate production factors through the cycle of cost management and cumulative causal effects, thereby realizing factor innovation. Zheng (2017) conducted an empirical study on the nonlinear impact of technological innovation on urbanization and concluded that technological innovation had become an important factor in promoting urbanization in China. Meanwhile, urbanization can provide the necessary basic support for technological innovation, and the agglomeration effect brought by urbanization can bring positive externalities to technological progress (Carlino et al., 2017). Moreover, studies have shown that there is a coordinated relationship between urbanization development and technological innovation. That is, technological innovation is the driving force of urbanization, and urbanization provides a broad platform for technological innovation (Gan, 2014), and there is a two-way positive relationship between the two, and they are gradually optimized in space (Tian et al. 2017).
To maintain the coordinated development of urbanization and human society, the Chinese government has announced that priority should be given to green production and green consumption in the process of urbanization construction. Therefore, the optimal outlet of urbanization development lies in adopting a new technology innovation mode based on the value of sustainable and green development, namely called green technology innovation (Wan and Huang 2004). Braun and Wield (1994) first proposed the concept of “green technological innovation,” which meaning basically referred to following the principles of ecology and the laws of ecological economy, saving resources and energy, avoiding, eliminating or mitigating ecological environmental pollution and damage, and minimizing ecological negative effects (Peng et al. 2020). Different from traditional technology innovation, green technology innovation is understood as an inclusive concept, intersecting with modern technologies, such as Nanotechnology, Information Technology, or Bioengineering Technology (Lee et al. 2015). Green innovation can also increase the competitive advantage of enterprises through green production (Zameer et al., 2019). Guo et al. (2020) pointed out that the purpose of green technology innovation is to deal with comprehensive sustainable challenges, including environmental damage, unreasonable industrial structure, people’s livelihood issues, etc., rather than environmental issues. Then, scholars began to explore the relationship between green technological innovation and urbanization. Chen and Ding (2015) found that green technology innovation realizes the intelligent of consumer market through the completion of productization and industrialization, which satisfies the residents’ pursuit of high-quality life, and thus improving the quality of urbanization. Wu et al. (2019a, b) concluded that green technology innovation improves the energy utilization efficiency, thus optimizing the energy consumption structure and promoting the transformation of urbanization from quantity to quality. Liu et al. (2016) proposed that constant green technology innovation can promote the development of information industry, which will penetrate into the fields of municipal, transportation, education, and medical care, so as to optimize the construction of urban infrastructure. Luo et al (2019) pointed out that the increased efficiency of green technology innovation is the main driving force for China’s strategic emerging industries and the sustainable development of urbanization.

Existing literature has discussed the relationship between green technological innovation and urbanization. However, few studies have explored the impact mechanism of technological innovation on urbanization and the perspective of urbanization types. Therefore, further research is needed from a more comprehensive perspective. This paper attempts to supplement previous research by analyzing the direct and indirect effects of green technological innovation on urbanization. And we subdivide urbanization into population urbanization, industrial urbanization and ecological urbanization, and further explore the impact of green technological innovation on different types of urbanization.

The impact mechanism of green technological innovation on urbanization

Direct effect

The improvement of material value and environmental quality brought by green technology innovation constitutes the important driving force for high-quality development of urbanization. Firstly, green technology innovation promotes the improvement of economy, thus raising residents’ income level and living standard, and directly improving residents’ living conditions. Secondly, the high-tech industry is further improved based on the marketization of green technology innovation, which is conducive to promote the city-industry integration, and thus gradually perfecting urban functions. Thirdly, green technology innovation is an effective way to control environmental pollution at source through renovating high-pollution industries, which will improve the ecological level.

Indirect effect

Green technology innovation can recombine capital with factors such as knowledge, business model, and institutional environment, which can indirectly affect urbanization.

Industrial structure optimization effect

Green technology innovation promotes the high-end industrial chain development, including front-end technology research and design and back-end service and market (Zhang and Huang 2015). More importantly, urbanization is to guide the upgrading of production and consumption through the advanced industrial structure, so as to achieve high value-added economic growth (Guo et al. 2021). Therefore, being an important support for urbanization development, the optimization of industrial structure is bound to lead to the improvement of urbanization (Chenery and Syrquin 1975).

Foreign investment effect

With the in-depth development of China’s opening up, the entry of foreign capital has brought a considerable number of employment opportunities and fiscal revenue to China, and promoted the development of China’s urbanization (Wang et al. 2021). Green technology innovation influences the quality of foreign investment by enhancing China’s position in the global value chain (Bai et al., Luo et al., 2021). High-quality foreign investment flows freely in industrial sectors and regions, thereby further promoting the development of urbanization in coordination, openness and sharing (Sang and Zhang 2018).
**Energy consumption effect** The green technological breakthroughs in clean energy exploitation and utilization directly increase the supply and consumption of clean energy, thus improving the energy consumption structure. The optimized energy consumption structure reduces the dependence of urbanization development on fossil energy (Wu et al., 2019a, b), which is conducive to eliminate the tail effect of energy consumption in urbanization development and realize the sustainable development of urbanization.

**Informatization development effect** Green technology innovation is the dominant factor in informatization development. Informatization development enhances the radiating and driving role of central cities, which is conducive to the coordinated development of urban agglomeration. At present, China’s smart city pilot projects have been launched in many cities. It is obvious that informatization development will become an important trend in urbanization development.

The mechanism of green technology innovation affecting urbanization is shown in Fig. 1. This paper is devoted to analyzing both the direct and indirect impact of green technology innovation on urbanization, and we have the following hypotheses:

**H1:** Green technology innovation has a direct impetus to urbanization development.

**H2:** Green technological innovation has a direct impact on population urbanization, industrial urbanization and ecological urbanization.

**H3:** Industrial structure optimization, improved foreign investment, energy consumption structure optimization and informatization development play an intermediary role in promoting urbanization through green technology innovation.

**Methodologies**

**Model specification**

This paper aims to investigate the impact of green technological innovation on urbanization and its impact mechanism. First, we use a panel regression model to explore the direct impact of green technological innovation on urbanization. Among them, the selection of fixed effects and random effects models is tested by the Hausman method. Additionally, in order to correct heteroscedasticity and autocorrelation, we use a more comprehensive FGLS regression model to test the data to improve the robustness of the results. Second, we further examined the indirect impact of green technological innovation on urbanization through the mediation effect model.

In order to investigate the direct effect of green technology innovation on urbanization, this paper constructs a regression model as shown in Eq. (1):

\[ URB_{it} = \alpha_i + \beta_1 GTI_{it} + \sum \beta_n Control_{it} + \eta_i + \mu_t + \epsilon_{it} \]  

(1)

where \( i \) represents the province and \( t \) represents the year. \( URB_{it} \) represents the level of urbanization, \( GTI_{it} \) represents the level of green technology innovation, \( Control_{it} \) are a series of exogenous control variables, including infrastructure construction (INFRA), education development (EDU), marketization (MARKET), and financial development (FIN). \( \eta_i \) and \( \mu_t \) respectively represent the annual and individual effects, \( \epsilon_{it} \) is the random disturbance term.

The mechanism of green technology innovation affecting urbanization is further tested applying the mediating effect method. The models as shown in Eqs. (2)–(4) are constructed:
$URB_{it} = \alpha_{it} + \beta_1 GTI_{it} + \sum \beta_m Control_{it} + \eta_i + \mu_t + \epsilon_{it}$  \hspace{1cm} (2)

$M_{it} = \gamma_{it} + \delta_1 GTI_{it} + \sum \delta_m Control_{it} + \eta_i + \mu_t + \epsilon_{it}$  \hspace{1cm} (3)

$URB_{it} = \sigma_{it} + \theta_1 GTI_{it} + \rho M_{it} + \sum \theta_m Control_{it} + \eta_i + \mu_t + \epsilon_{it}$  \hspace{1cm} (4)

where $M_{it}$ represents the mediating variables, including industrial structure optimization ($STRU$), foreign investment ($FDI$), energy consumption structure ($ESTR$), and informatization development ($INFOR$). Generally speaking, when the parameter $\gamma_1$ in Eq. (2) is significantly positive, and if the parameter $\delta_1$ in Eq. (3) and parameter $\rho$ in Eq. (4) are significantly positive, it indicates that $GTI$ has a positive mediating effect on $URB$ through mediator $M$.

### Variable declaration

Urbanization (URB). The current urbanization of China has entered into a new development stage in which not only the improvement of urbanization rate is required, but also the achievement of economic intensive development, industry optimization, the happiness of people and livable environment. Therefore, the traditional single index can no longer meet the requirement of measure. We refer to the research of Xu and Wang (2018) and construct an index system of urbanization based on the three principles of people-oriented, city-industry integration and green ecology, as shown in Table 1. Then, we use the entropy method to measure the level of urbanization in the new city. Entropy method was originally proposed by Shannon (1948), used as a measure of uncertainty in information processing. It has been widely used in recent studies, such as the research of Hashim et al. (2020), using entropy method in ecological efficiency. Therefore, it can be said that this method is suitable for information processing. In this paper, the improved entropy method is used to determine the weight of each indicator and then measure the level of urbanization.

The calculation method is as follows:

Firstly, the dimensionless treatment is carried out on each indicator. The formulas for positive and negative indicator are respectively shown as Eqs. (5) and (6):

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$  \hspace{1cm} (5)

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$$  \hspace{1cm} (6)

Secondly, calculate the proportion of index $x_{ij}$ of index $j$:

| Target                              | Criterion                   | Factor                           | Indicator                                                                 |
|-------------------------------------|-----------------------------|---------------------------------|---------------------------------------------------------------------------|
| Urbanization development            | People-oriented             | Basic life                      | Per capita GDP, average wages of urban staff                              |
|                                     |                             | The guarantee of people’s livelihood | The proportion of urban endowment insurance participants, the number of health technicians per ten thousand people, the proportion of education expenditure in fiscal expenditure |
|                                     |                             | Coordinating urban and rural development | Proportion of urban population, urban and rural income ratio, urban and rural consumption ratio |
| City-industry integration           | Structure optimization      | The proportion of non-agricultural industries, fixed investment in high-tech industries |
|                                     | Quality improvement         | The proportion of urban employment personnel with college degree or above, energy consumption per GDP, the number of granted patent approval per 100 million GDP |
| Green ecology                      | Environmental investment    | Per capita environmental infrastructure investment |
|                                     | Urban landscaping           | Per capita public green areas, coverage rate of urban green areas |
|                                     | Pollution treatment         | Comprehensive utilization rate of fixed waste, hazard-free treatment rate of household garbage |
Thirdly, calculate the information entropy of index $j$:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} \left( p_{ij} \times \ln p_{ij} \right)$$  \hspace{1cm} (8)

Fourthly, calculate the coefficient of difference of index $j$:

$$g_j = 1 - e_j$$  \hspace{1cm} (9)

Fifthly, ascertain the weighing of each evaluation indicator:

$$w_j = \frac{g_j}{\sum_{j=1}^{m} (g_j)}$$  \hspace{1cm} (10)

Finally, obtain the comprehensive evaluation value of urbanization:

$$z_i = \sum_{j=1}^{m} w_j \times x_{ij}$$  \hspace{1cm} (11)

Green technology innovation (GTI). The measurement of green technology innovation mainly includes the single index method, evaluation index system method and efficiency measure method (Zhang 2015; Sun et al. 2017). Referring to Luo and Liang (2016), this paper divides the process of green technology innovation into two stages, including green technology development stage and green technology achievement transformation stage, and constructs the input–output evaluation index system of green technology innovation as shown in Table 2. The super-efficiency DEA method is used to measure the level of green technology innovation.

**Industrial structure optimization (STRU)** Referring to Cai and Xu (2017), we use the ratio of the output value of the tertiary industry and the secondary industry to characterize the industrial structure optimization effect.

**Foreign investment (FDI)** The effect of foreign investment is always measured by the proportion of foreign direct investment in GDP (Bai et al. 2020; Luo et al. 2021).

Energy consumption structure (ESTR) Increasing the proportion of natural gas consumption has become an important means to promote China’s green development of urbanization. According to the study of Xu and Wang (2018), we introduce the proportion of natural gas consumption in total energy consumption to measure the energy consumption effect.

Informatization development (INFOR) This paper uses the per capita sales value of computer, communication and other electronic equipment manufacturing industries to measure the informatization development effect.

Infrastructure construction (INFRA) INFRA is measured by urban road area per capita.

Education development (EDU) EDU is measured by the number of college students per thousand people.

Marketization (MARKET) Referring to Fan et al. (2011), we measure the degree of marketization from the perspectives of the relationship between government and market, the development of non-state-owned economy, the development of product market, the development of market intermediary organization and the legal system environment.

Financial development (FIN) The ratio of the loan balance of financial institutions to GDP is used to measure the level of financial development (Li et al. 2016).

Data sources

In view of the principle of data availability, this paper selects the 30 provinces in China over 2004–2019 as research sample, excluding the data of Tibet, Hong Kong, Macao, and Taiwan. The data are mainly collected from the “China Statistical Yearbook,” “China Population & Employment Statistics Yearbook,” “China Statistical Yearbook on Science and Technology,” “China Statistical Yearbook on Environment,” and “China Energy Statistical Yearbook.” The mean value

| Stage                                      | First-class indicator | Second-class indicator                          |
|--------------------------------------------|-----------------------|------------------------------------------------|
| Green technology development               | R&D input             | Full-time equivalent of R&D personnel, internal expenditure on R&D, expenditure on technology introduction and transformation, expenditure on new product development |
|                                            | Energy input          | Energy intensity                                 |
|                                            | Intermediate output   | Patent application quantity                      |
|                                            | Desirable output      | Sales revenue of new products                    |
|                                            | Undesirable output    | Carbon emission                                  |

Table 2: Input–output system of green technology innovation
method is used to make up for the missing data of some statistical indicators. Meanwhile, we take 2004 as the base period to deflate relevant nominal data. Table 3 presents the statistical description of the variables used in our analysis.

## Results and discussions

### The direct effect of green technology innovation on urbanization

Table 4 reports the estimated results of Eq. (1). In Table 4, model (1) is the estimation result of only incorporating explanatory variables. Models (2)~(5) are the estimation results controlling infrastructure construction, education development, marketization, and financial development step by step. It is noted that heteroscedasticity and first-order sequence correlation exist among variables through the test of the panel data, so we refer to the study of Le (2021) using the panel feasible generalized least squares (FGLS) estimation method to improve the robustness in model (6).

As shown in model (1), the coefficient of $GTI$ is positive at significant level of 1%, indicating that green technology innovation can promote urbanization development, which is completely consistent with hypothesis 1. With successively incorporating control variables, the estimated effects of green technology innovation on urbanization are still significantly positive, which implies that infrastructure construction, education development, marketization, and financial development are effective in promoting urbanization development. Compared with model (5), although the estimated coefficients of the FGLS method in the model (6) are quite different, the significance of each variable remains unchanged.

It’s obvious that the coefficient of $GTI$ is larger than any other control variables, indicating that the most effective path to promote urbanization development is to develop green technology innovation. Indeed, in recent years, China has made great efforts to promote the development of green technology innovation. Specifically, relevant government plans and policies have been continuously introduced, investment in R&D for green technology innovation has grown steadily, and China’s innovation environment for green technology has been increasingly optimized. Moreover, China’s green technology innovation can promote the green and high-quality development of urbanization by improving the quality of residents’ life, reducing pollution emissions and increasing economic effects. Therefore, the hypothesis 1 is verified.

### Table 3 Statistical description of variables

| Variable type       | Variable name | Meaning of variable | Mean value | Standard deviation | Minimum value | Maximum value |
|---------------------|---------------|---------------------|------------|--------------------|---------------|---------------|
| Explained variable  | $URB$         | Urbanization        | 0.3400     | 0.0704             | 0.1897        | 0.5978        |
| Core variable       | $GTI$         | Green technology innovation | 0.5851     | 0.2486             | 0              | 1             |
| Intervening variable| $STRU$        | Industrial structure optimization | 1.1640     | 0.6373             | 0.5270        | 5.2340        |
|                     | $FDI$         | Foreign investment  | 2.2283     | 1.7899             | 0.0382        | 10.2363       |
|                     | $ESTR$        | Energy consumption structure | 0.0622     | 0.0705             | 0.0000        | 0.4282        |
| Control variable    | $INFOR$       | Informatization development | 0.4197     | 0.6997             | 0.0000        | 3.2776        |
| INFRA              | $INFRA$       | Infrastructure construction | 13.9003    | 4.9446             | 5.1800        | 32.3300       |
| $EDU$              | $EDU$         | Education development | 23.6811    | 10.0528            | 7.4520        | 68.9700       |
| MARKET             | $MARKET$      | Marketization       | 6.5786     | 1.9292             | 2.3300        | 11.7100       |
| FIN                | $FIN$         | Financial development | 1.2195     | 0.4393             | 0.5329        | 2.5847        |

### Table 4 Empirical results with the direct effect

|                         | Model (1)       | Model (2)       | Model (3)       | Model (4)       | Model (5)       | Model (6)       |
|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $GTI$                   | 0.1480*** (17.99) | 0.1049*** (11.63) | 0.0487*** (5.43) | 0.0472*** (5.24) | 0.0490*** (5.51) | 0.0118*** (2.46) |
| $INFRA$                 | 0.0047*** (8.90)  | 0.0029*** (6.09)  | 0.0026*** (4.98) | 0.0024*** (4.47) | 0.0017*** (6.80) | 0.0005*** (6.72) |
| $EDU$                   | 0.0012*** (12.53) | 0.0011*** (12.15) | 0.00088 (1.38)  | 0.0147*** (2.29) | 0.0296*** (6.00) | 0.0005*** (6.62) |
| $MARKET$                | -0.0065*** (-3.99) | 0.0005*** (5.73)  | 0.0178*** (26.38)| 0.2153*** (18.86)| 0.1970*** (13.96)|                |
| _cons                   | 0.2518*** (23.27) | 0.2122*** (18.14) | 0.1807*** (29.69)| 0.1785*** (26.38)| 0.2153*** (18.86)| 0.1970*** (13.96)|
| $N$                     | 480             | 480             | 480             | 480             | 480             | 480             |
| Model selection         | $RE$            | $RE$            | $FE$            | $FE$            | $FE$            | $FGLS$          |

*, **, and *** represent significance at 10%, 5%, and 1% level, respectively; the $t$-test is shown in ( )
For control variables, the coefficients of INFRA, EDU, FIN, and MARKET are all positive at significant level of 5%, indicating that the improvement of the infrastructure construction, education development, financial development, and marketization have significantly promoted the level of urbanization. Firstly, infrastructure construction is the leading capital for urbanization development. In recent years, the problem of “urban diseases” caused by traditional urbanization has received widespread attention. Pilot projects for the construction of “sponge cities” and “smart cities” have been fully launched, and infrastructure construction has gradually developed in the direction of intensive, smart, green, and low-carbon, which strongly supports the process of new urbanization. Secondly, educational development is an important support for urbanization. On one hand, education can generally improve the cultural level of residents and alleviate the dual structure in the process of traditional urbanization. On the other hand, education can promote the accumulation of human capital and the improvement of human capital quality, which is conducive to the development of knowledge-intensive industries and thus promotes The industrial structure was optimized and upgraded. Thirdly, the role of financial development level in promoting urbanization is second only to green technological innovation. The reason may be that in the process of urbanization, a large number of people have poured into cities and towns, which has brought huge investment and housing needs. Meanwhile, the government also needs a lot of funds for the construction of urban infrastructure. In addition, finance promotes the improvement of urbanization by supporting infrastructure construction and some industries. Finally, the increase in the degree of marketization can create a good environment for innovation, effectively promote the free flow of production factors and optimize the allocation, and provide a favorable market foundation for the improvement of the quality of urbanization.

According to the three principles of urbanization, namely people-oriented, city-industry integration and green ecology, we subdivide urbanization into population urbanization (POPURB), industrial urbanization (STRURB), and ecological urbanization (ECOURB), so as to explore the effect of green technology innovation on these dimensions of urbanization. The results are shown in Table 5.

The coefficients of GTI are all significantly positive at the 1% level, suggesting that the improvement of green technology innovation has significant promoted population urbanization, industrial urbanization and ecological urbanization. The impact of green technology innovation on population urbanization is significantly higher than that on ecological urbanization, indicating that at present, green technology innovation mainly has a positive impact on the production process, and the positive effect on the field of environmental investment is limited. Specifically, due to the improvement of environmental quality and economic growth, green technology innovation improves the livability of cities and increases the happiness of urban residents, which is conducive to promoting population urbanization. The role of green technological innovation in promoting industrial urbanization is consistent with our expectations. The main reason is that the industrialization and marketization of green technology innovation contribute to the development of high-tech industries, thus optimizing the industrial structure and promoting industrial transformation and upgrading, which has a significant promoting effect on the integration of industry and city. The possible reason for the limited role of green technology innovation in promoting ecological urbanization lies in that the innovative achievements has not been effectively transformed in the application of green technology. To sum up, the hypothesis 2 is verified.

### The indirect effect of green technology innovation on urbanization

Based on the scatter diagram, we intuitively investigate the transmission mechanism of green technology innovation to urbanization, as shown in Fig. 2. It is obvious that there is a significantly positive relationship between green technology innovation and urbanization. However, as shown in

| Table 5 Empirical results with three dimensions of urbanization |
|-------------------|------------------|------------------|------------------|
|                  | Population urbanization | Industrial urbanization | Ecological urbanization |
| GTI              | 0.0356*** (9.73) | 0.0329*** (4.75) | 0.0173*** (4.73) |
| INFRA            | 0.0006* (2.39) | 0.0053*** (11.59) | 0.0004 (1.40) |
| EDU              | 0.0033*** (13.04) | 0.0037*** (9.55) | 0.0025*** (8.65) |
| FIN              | 0.0236*** (5.24) | -0.0027 (-0.63) | 0.0321*** (11.47) |
| MARKET           | 0.0041** (5.18) | 0.0005 (0.27) | 0.0069*** (8.16) |
| _cons            | 0.1588*** (14.58) | 0.1853*** (11.20) | 0.1417*** (17.44) |
| N                | 480              | 480              | 480              |
| Model Selection  | FGLS             | FGLS             | FGLS             |

*, **, and *** represent significance at 10%, 5%, and 1% level, respectively; the t-test is shown in ()
Fig. 2a, the upgrading of industrial structure does not rise significantly with the improvement of green technology innovation, the same as the relationship between industrial structure optimization and urbanization. Therefore, it is possible that industrial structure optimization plays a weak intermediary role in the impact of green technology innovation on urbanization.

Based on the mediating effect method, we use Eqs. (3) and (4) to examine the mediating role of industrial structure optimization effect, foreign investment effect, energy consumption structure effect and informatization development effect in the impact of green technology innovation on urbanization. The estimated results of Eq. (3) are presented in models (1), (3), (5), and (7) in Table 6, respectively, and the estimated results of Eq. (4) are reported in models (2), (4), (6), and (8) in Table 6, respectively.

**Industrial structure optimization effect** The coefficient of \( GTI \) in model (1) is 0.2289, which means for each additional unit of \( GTI \), \( STRU \) will increase by 0.2289 units, that is, the green technology innovation has a significantly positive impact on industrial structure optimization (model (1) in Table 6). The coefficient of \( STRU \) in model (2) is 0.0504, which means for each additional unit of \( STRU \), \( URB \) will increase by 0.0504 units, i.e., industrial structure optimization plays a positive role in promoting urbanization (model (2) in Table 6), which indicates that the mediating effect of industrial structure optimization effect on promoting

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**Fig. 2** Scatter diagram of the transmission mechanism. a Industrial structure optimization effect. b Foreign investment effect. c Energy consumption effect. d Informatization development effect
There is no doubt that the economic growth model of China is at the transition stage, and the development of industry and green technology innovation still have strong vitality. Green technology innovation is conducive to the optimization of industrial structure. As a result, the positive mechanism of industrial structure optimization in promoting urbanization development has been fully demonstrated.

**Foreign investment effect** The coefficient of $GTI$ in model (3) is 0.8162, which means for each additional unit of $GTI$, FDI will increase by 0.8162 units, that is, green technology innovation has remarkably enhanced the foreign investment level (model (3) in Table 6). The coefficient of $FDI$ in model (4) is 0.0333, which means for each additional unit of $FDI$, URB will increase by 0.0333 units, i.e., the foreign investment plays a significant positive role in promoting urbanization (model (4) in Table 6), which indicates that green technology innovation is conducive to the improvement of foreign investment level, thus promoting urbanization development. Hence, the mediating effect of foreign investment effect on promoting urbanization development is notable. On one hand, the demographic dividend is gradually weakening in China, which results in the transfer of foreign investment is becoming the norm gradually (Li et al. 2016). The green technology innovation provides a technical support for the optimization of investment environment, thus increasing the attraction to foreign direct investment. On the other hand, foreign investment structure in China has been continuously upgraded. For example, in 2017, the annual actual absorption of foreign capital in high-tech industries increased by 61.7% in China, accounting for 28.6% of the total, and a 9.5% increase for the same period last year (Wang 2018). The effect of knowledge spillover and structural upgrading caused by the improvement of foreign investment quality further promote the urbanization.

**Energy consumption effect** The coefficient of $GTI$ in model (5) is 0.0704, which means for each additional unit of $GTI$, ESTR will increase by 0.0704 units, that is, green technology innovation has a significant impact on energy consumption. The coefficient of $ESTR$ in model (6) is 0.0397, which means for each additional unit of $ESTR$, URB will increase by 0.0397 units, i.e., the energy consumption structure optimization has remarkably promoted the urbanization level (model (6) in Table 6), which indicates that green technology innovation is helpful to the upgrading of energy consumption structure, thus promoting urbanization level. Therefore, the mediating effect of energy consumption effect promotes urbanization development. The green technology innovation not only can improve the tackling efficiency of environmental pollution caused by excessive energy consumption but also can promote the
use of clean energy such as natural gas. In recent years, the proportion of clean energy consumption has a upward trend in China, e.g., natural gas consumption accounts for 7.92% of the total in 2019, exceeding the 2.5% in 2005, although China's energy consumption structure is still dominated by the coal-based energy. To sum, the optimization of energy consumption structure is conducive to alleviating pollution emissions and improving the quality of economic growth, so as to strongly ensure the construction of urbanization.

**Informatization development effect** The coefficient of $\text{GTI}$ in model (7) is 0.3491, which means for each additional unit of $\text{GIT, INFOR}$ will increase by 0.3491 units, that is, green technology innovation has significantly increased the informatization development level (model (7) in Table 6). The coefficient of $\text{INFOR}$ in model (8) is 0.0679, which means for each additional unit of $\text{INFOR, URB}$ will increase by 0.0679 units, i.e., the informatization development has remarkably promoted the urbanization level (model (8) in Table 6), which infers that the mediating effect of informatization development effect on promoting urbanization development is significant. The development of green technology leads to the flourish of the IT industries in China such as 5G, cloud computing, big data, and artificial intelligence, which is helpful to the integration of digital economy and real economy and the development of smart city. At the same time, the development of smart livelihood, smart government, and smart transportation further stimulates the demand for information consumption, forming a virtuous circle of mutual benefit development of informatization and urbanization.

Furthermore, the model (9) in Table 6 is the estimated result of incorporating intervening variables in the same equation. The coefficient of $\text{GTI}$ is 0.0375, which further indicates that the indirect effect of green technology innovation on urbanization is notable. That is to say, green technology innovation has indirectly accelerated the construction of urbanization by attracting foreign investment, optimizing the structure of energy consumption and promoting the development of informatization, which indicates that the Hypothesis 3 is verified.

**Further discussions**

In recent years, many scholars have measured urbanization and green technological innovation by using different methods (Piano et al. 2019; Ahmed et al. 2020; Yu, 2021). Moreover, they explored the relationship between the two, also, the impact of green technological innovation on urbanization (Amin et al. 2020; Liu and Tian 2020; Sahoo and Sethi, 2021; Khurshid et al. 2021). But few study makes an in-depth exploration of the specific mediation mechanism among green technological innovation and urbanization. Therefore, new study was pivotal to overcome these issues and explore the coordinated development of natural resources, financial development and ecological efficiency. In this study, we subdivide urbanization into population urbanization, industrial urbanization and ecological urbanization, and further investigate the impact of green technological innovation on different types of urbanization. In addition, we conducted a mediating effect analysis on perspective of industrial structure, foreign investment, energy consumption, and information development, further than previous studies.

The results from the study has shown that green technological innovation not only directly promotes the development of urbanization, but also has a significant indirect impact on urbanization by influencing the industrial structure optimization, the foreign investment, the energy consumption structure, and the informatization development during the time period under analysis. This is similar to the studies of Gu and Zhu (2019) and Jiang et al. (2019). They also verified that green technological innovation is a significant driving force for urbanization. However, the study of Hao and Wu (2018) showed that the connection between the urbanization process and technological innovation in western China is insignificant, while the effect of technological innovation on the urbanization of the central region was significant. The reason may be that the western China is vast and sparsely populated, and the urbanization process is slow, so it cannot keep up with the growth rate of technological innovation. Additionally, the effect of green technological innovation on different types of urbanization varies greatly, which is also the major difference between this study and previous studies.

**Conclusions and policy implications**

This paper explores the direct and indirect effects of green technological innovation on urbanization, and the main conclusions are summarized as follows. Green technological innovation not only directly promotes the development of urbanization, but also has a significant indirect impact on urbanization by influencing the industrial structure optimization, the foreign investment, the energy consumption structure, and the informatization development. Moreover, green technology innovation has significant positive effects on industrial urbanization, ecological urbanization, especially population urbanization. These findings are understandable because that green technology innovation aims at environmental friendliness and economic development. On one hand, environmental pollution problems in the development of urbanization can be alleviated through innovative technologies, achieving the green application of green innovative
results and further the development of ecological urbanization. On the other hand, the introduction of technological innovation mode can stimulate economic growth and raises the level of residents’ income, so as to improve the development of population urbanization. In addition, the high-tech industrial system is well established based on the industrialization and marketization of green technology innovation, which drives the improvement of industrial urbanization. The comprehensive impact of green technology innovation on population urbanization, industrial urbanization and ecological urbanization makes it more effective in promoting the development of urbanization.

Our findings, especially the mechanism through which green technology innovation affects urbanization, may be of significant practical utility to policymakers. Firstly, focusing on improving the efficiency of green technology innovation and giving play to the supporting role of green technology innovation in leading the development of new urbanization. Specifically, it includes gathering of innovative resources, strengthening the support of talents, funds and market elements, encouraging the development of green financial product innovation, and increasing the enthusiasm of enterprises for green technology research and development. In addition, government should continue to carry out diversified pilot projects such as carbon emissions trading and renewable energy trading to achieve the unification of environmental and economic benefits of green technology innovation. Secondly, promoting the optimization and upgrading of the industrial structure, and realizing the development of “industry-city integration” in urbanization. The development of urbanization is a systematic project. It is necessary to proceed from the overall situation and coordinate the three major structures of space, scale, and industry. While optimizing the spatial layout of productivity, relevant department should adjust and optimize the urban industrial structure, aiming at high-end, intelligent and green industries, and promoting the urbanization development model of industry-city integration with human beings at the core. Thirdly, optimizing the structure of foreign investment and formulating differentiated investment strategies for the development of urbanization. Specifically, the local government should relax market access and encourage foreign-invested enterprises to enjoy the same treatment as domestic-funded enterprises in the city. Efforts will be made to create a good business environment, improve government administrative efficiency, and enhance the facilitation of foreign investment. Meanwhile, we will formulate differentiated investment strategies based on regional development strategies and development characteristics. Fourthly, increasing the use of clean energy and realize the low-carbon development of urbanization. The government should increase the investment in R&D funds and talents of clean energy, so that solar energy, bioenergy and other clean energy can be stable supplied. Making up for the natural gas supply gap, increasing the installed capacity of clean energy, reducing the vacancy rate of energy devices, and promoting the integrated development of the energy industry and other industries in accordance with local conditions. Finally, promoting the construction of smart cities must be market-oriented, rely on scientific and technological innovation to promote the interconnection of scientific research institutions and enterprises, form a trinity of industry-university-research smart construction system, and then promote cities to become knowledge centers and innovation incubators.

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Author contribution Yingzhi Xu provided the article’s ideas, methods, and the framework of the whole study; Ruijie Zhang and Xiaomin Fan were responsible for English text content and polish; QiuTong Wang was responsible for the consolidation of data and preliminary work of the model.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

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