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Short-Run And Long-Run Green Knowledge Spillovers In Turkey

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ABSTRACT

The importance of green economic growth strategies driven by environmentally friendly technologies has gained recognition due to climate change and environmental pollution. In response, countries began to focus on transitioning to competitive, green-based production technologies. Knowledge spillovers, or the transfer of green knowledge between firms, can help measure the effectiveness of such transitions. The study aims to estimate the short-run and long-run spillovers from green technologies to selected technology fields (biotechnology, medical technology, nanotechnology, pharmaceutical technology, and ICTs) using Türkiye as a case study. The data consists of patent registrations in green technologies and selected technology fields for the period 1988-2020. The method uses the ARDL Model, with patent registrations in green technologies as independent variables and patent registrations in selected technology fields as dependent variables. The results demonstrate that a significant long-run co-integration exists only between green technologies and nanotechnology, indicating a successful green transition in this field. Positive short-run effects are observed in nanotechnology, ICTs, pharmaceutical technologies, and biotechnologies, though these are still emerging. No significant spillovers are found in medical technologies, highlighting the need to prioritize green transition in the healthcare sector, particularly through waste management and greener medical products.

Keywords: Knowledge Spillovers, Green Knowledge Spillovers, Green Technologies, Time Series Analysis.

JEL Classification Codes: C32, D83, O44

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INTRODUCTION

Global greenhouse gas emissions increased dramatically due to rising production levels and energy demand. In developing countries, it is generally driven by increased fossil fuel emissions, closely tied to the reliance on non-renewable energy sources in production and international trade. Indeed, it is expected that developing countries will account for 65% of global greenhouse gas emissions by 2030 (Roeth and Wokeck, 2011). The agriculture, food, energy, and construction sectors account for approximately 80%, and the food industry is responsible for 33% of greenhouse gas emissions (Kumral et al., 2024).

Knowledge spillovers—the transfer of new knowledge between firms and industries—are valuable indicators of whether industries are effectively progressing in green transition. Knowledge spillovers are critical for fostering subsequent innovations (Nie et al., 2021) and occur when knowledge reaches a certain level of specialization and becomes widely shared. Technological advancements made today are often built on information developed by

both the originating firm and other firms, from the same or previous periods. In other words, when the benefits of new knowledge cannot be fully captured over the long term, knowledge tends to spill over, between firms within the same industry—a phenomenon known as inter-industry or horizontal spillovers—and between different industries—a phenomenon known as intra-industry or vertical spillovers (Kaiser, 2002). Empirical studies by Ponds et al. (2009) and Montoro-Sanchez et al. (2011) show that knowledge spillovers among firms and industries enhance innovation.

Green knowledge spillovers offer a way to evaluate progress in the green transition. As the green transition unfolds, green knowledge spillovers will naturally emerge. For instance, the absence of green knowledge spillovers in an industry indicates that the industry has not yet achieved a green transition. Conversely, the presence of green knowledge spillovers suggests that an industry has successfully undergone the green transition.

Green technologies refer to environmentally friendly technological advancements designed to reduce the

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adverse impacts of climate change and economic activities on the environment. Green technologies encompass a range of innovations aimed at minimizing environmental impact, and their influence extends across multiple fields. Examining the knowledge spillover effects of green technologies can provide insight into the green transition process at the industry level.

The literature commonly discusses the green technological transition process in relation to production and growth (Danish and Ulucak, 2020), regional or spatial economic convergence (Shang et al., 2022), employment (Aldieri and Vinci, 2018), foreign trade (Bai et al., 2023), carbon emission (Jiao, et al., 2020; Pan et al., 2021), and other macroeconomic aggregates. While these discussions often focus on macroeconomic outcomes, a crucial factor in evaluating the success of the green transition is the impact of knowledge spillovers. Moreover, while much of the literature (Guo et al., 2020; Jiao et al., 2020) focuses on the direct effects of green technologies on environmental sustainability, carbon emissions, and economic growth, less attention has been given to their broader influence across other sectors. Green technologies, by their nature, have the potential to transform multiple industries beyond their immediate scope. However, most studies have concentrated on their direct impact on environmental sustainability, with less emphasis on the broader influence of knowledge spillovers across various technology fields (Aldieri and Vinci, 2018; Aldieri et al., 2019). Shengrong and Liandwen (2019) indicate that green technology innovations have a cyclical cumulative effect, meaning that lagged values of green technology innovations have positive impacts on current green technology innovations. Similarly, Colombelli and Quatraro (2019) indicate that green technologies constitute heterogeneous sources of knowledge, especially in complementary and related technology fields, due to their highly varied structures. Aldieri et al. (2019) highlight that green innovative technologies generate significant knowledge spillovers. Similarly, Barbieri et al. (2020) emphasize that green technologies, more complicated and innovative than non-green technologies, have a broader and more substantial effect on the development of new technologies, resulting in even larger and more widespread spillovers.

The study aims to analyze and differentiate knowledge spillovers from green technologies to a wide range of technology fields in Türkiye, utilizing patents in OECD selected technologies: environmental (or green) technologies, biotechnologies, medical technologies, nanotechnologies, pharmaceutical technologies,

information and communication technologies (ICTs), and artificial intelligence (OECD Data Explorer). In this study, all selected technology fields from OECD are included, except for artificial intelligence, due to the insufficient data on AI in Türkiye. Türkiye was chosen as a case in this study because it prioritizes green transition in its top policy documents, such as the Twelfth Development Plan. In this plan, the chemistry, pharmaceuticals, and medical sectors were identified as priority sectors, and the need for a green transition was emphasized.

The main contributions of this study to the literature are as follows: it examines the green transition through the lens of technology policies. It analyzes green technology spillovers between priority sectors, both in the short and long run. It offers evidence-based policy to achieve a cost-effective green transition, as outlined in Türkiye's top-level policy documents. The study provides a new perspective on the sectoral dynamics of the green transition, particularly through the long-term knowledge spillovers identified in nanotechnology.

The next section outlines Türkiye's green transition policies, followed by a conceptual framework and econometric analysis. The paper concludes with policy recommendations for enhancing green transitions in selected sectors.

GREEN TRANSITION in TÜRKİYE

The creation of competitive production patterns based on the green transition is the main objective of the Twelfth Development Plan in Türkiye. The goal is to establish a competitive, green transition-based production system by 2053. In this context, the policy proposals aim to enhance economic efficiency through green transition in production, particularly in priority sectors (chemistry, pharmaceuticals and medical electronics, electrical equipment, devices, machinery, rail vehicles, and automotive in the manufacturing industry) and in priority development areas (agriculture and food, energy, defense, and tourism) (PSB, 2023). Accordingly, the policy proposals include supporting R&D activities and technology transfers for green technologies, designing green transition projects in Organized Industrial Zones, Industrial Zones, and small industrial sites, and offering sectoral incentives for green transition (PSB, 2023). Achieving this goal requires the development of green technologies, which are environmentally friendly innovations designed to reduce the adverse effects of climate change and economic activities on the environment, especially in sectors most responsible for carbon emissions.

According to UNCTAD patent statistics, the share of green technologies in total patent registrations was around 12% from 1988 to 2020. As shown in Figure 1, patent registrations for green technologies rank third from the last in conceptual classification. ICTs hold the highest share, followed by medical and pharmaceutical technologies, respectively. This indicates that the share of green technologies is greater than that of nanotechnologies and biotechnologies, but it is insufficient to ensure a green transition in Türkiye.

Green technologies can significantly enhance other technologies (OECD selected technologies) through various applications, including energy generation and storage, sustainable buildings and transportation, agricultural processing, wastewater treatment, drug and medical production, and medical waste management. Additionally, they play a role in developing ICT tools and services. Table 1 provides examples of green applications across selected OECD technologies (nanotechnologies, biotechnologies, pharmaceutical technologies, medical technologies, and information and communication technologies).

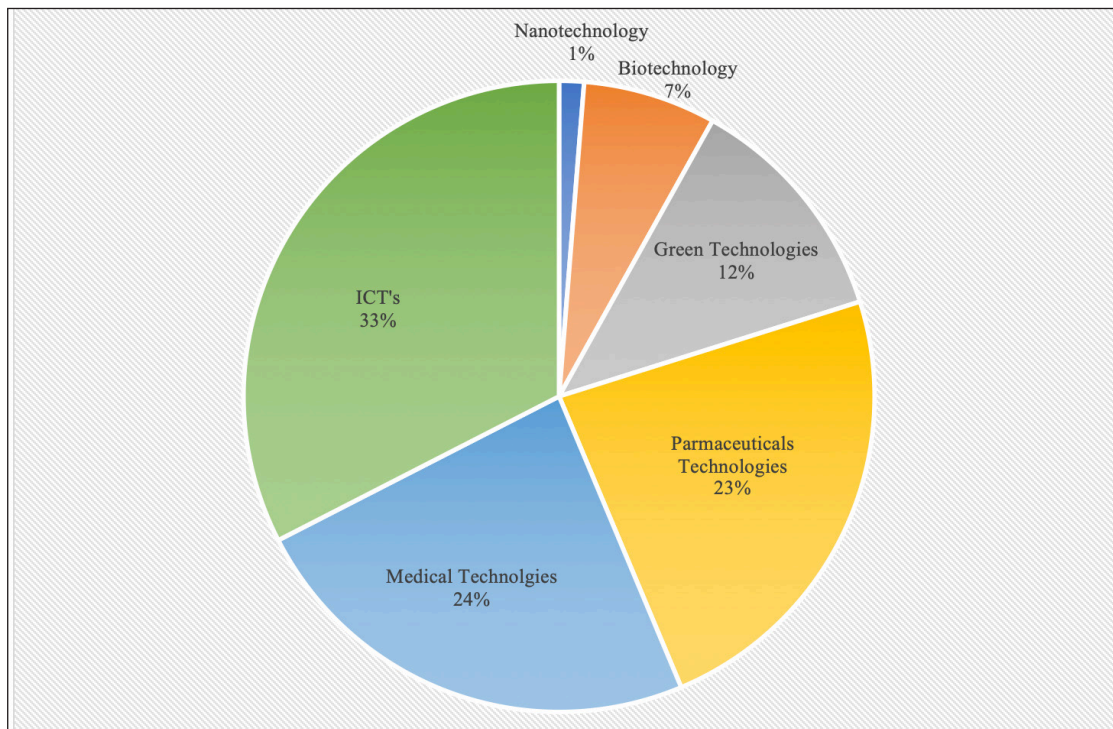


Figure 1: Share of Technology Fields by Patent Registrations in 1988-2020

Source: OECD.stat

THEORETICAL BACKGROUND and HYPOTHESIS

As outlined above, green technologies refer to a broad category of environmentally friendly technological advancements designed to reduce the negative impacts of climate change and economic activities on the environment. Green technologies include two subcategories: environmental and climate change management and mitigation technologies. Mitigation technologies also include seven sub-categories that are climate change mitigation technologies in ICTs (1), energy generation (2), wastewater treatment (3), disposal of greenhouse gases (4), transportation (5), buildings (6), and production or processing of goods (7) (OECD Data Explorer).

As green technologies advance, knowledge spillovers to other technology fields can enable technology fields to adopt greener practices, a process known as green transition. Therefore, investigating green applications and systems across different fields can help understand the potential for green knowledge spillovers in selected technological domains, as discussed below. For example, the linkage between **nanotechnologies** and green technologies can be examined through nanotechnological construction materials, energy applications, and environmental engineering. Accordingly, nano-technological construction materials such as

- building materials (e.g., recyclable and long-lasting concrete, steel, and insulation materials),
- protective surface applications (e.g., low-e coatings, UV protection, solar protection, dynamic glazing),
- self-cleaning coatings applications (e.g., self-cleaning paints, easy-to-clean surfaces),
- temperature regulation applications,
- insulation applications (e.g., insulating paint and panels),
- and energy storage applications (e.g., electrical energy by paper battery) as well as energy generation applications (e.g., solar glass, and semiconductor devices)

are environmentally friendly green applications. They reduce energy demand for heating, cooling, and lighting, decrease environmental pollution by minimizing energy losses, and lower carbon emissions (CO₂) by extending the lifespan of materials (Demirdöven and Karacar, 2013). Given that about 40% of the total energy produced globally is consumed in buildings, nano-technological construction materials can provide substantial energy savings (Kashef and Sabouni, 2010).

Additionally, nanoparticles used in water and groundwater treatment, soil reclamation, and air pollutant filtration are more environmentally friendly than traditional chemical applications, which may cause secondary pollution or damage habitat (Yakut and Karataş, 2021). Nanotechnologies, particularly in buildings, energy, and the environment, are closely linked to green and sustainable practices. As green nanotechnologies continue to advance, knowledge spillovers will likely facilitate their further expansion. In fact, the nanotechnology market is expected to grow by 30% annually during this decade (Theodore and Kunz, 2005).

Green **biotechnology** focuses on improving environmentally friendly, less costly, and more efficient production technologies (Ünver and Kurnaz, 2020). Waste-reducing biotechnologies, such as those that convert food waste into biofuel or animal feed, and biological wastewater treatment systems that are both highly efficient and cost-effective in reducing water pollution (Kharayat, 2012), as well as plant or agricultural biotechnologies that increase agricultural productivity through genetic modification or editing, all contribute to reducing carbon emissions from production and

consumption processes. As green nanotechnologies advance and contribute to sustainable practices, a similar trend is observed in green biotechnology, which focuses on developing environmentally friendly, cost-effective, and efficient production technologies. Genetically modified organisms, widely used in agriculture and the pharmaceutical industry, fall under the field of pharmaceutical biotechnology (Ünver and Kurnaz, 2020). The increased use of drugs and the resulting medical waste pose significant environmental challenges (Global Data Healthcare, 2017). Drug production generates substantial waste due to the toxic structures of many compounds (Brown, 2016), leading to the production of environmentally friendly drugs by altering the structures of existing drugs. For instance, green chemical applications aim to reduce waste, material use, energy requirements, and environmental risks during pharmaceutical production (Clark, 2008). In this context, technological advancements in agricultural, pharmaceutical, and ecological biotechnologies are closely related to green technologies. As green biotechnologies and green pharmaceutical technologies continue to evolve, knowledge spillovers will drive further expansion of these fields.

Pollution, particularly from waste, is primarily caused by healthcare and medical products and services worldwide. For instance, according to Diconsiglio (2008), **the healthcare** industry is the second-largest waste-generating sector in the United States (Kwakye et al., 2010). This is true in other countries as well, as healthcare waste must be treated before disposal due to the risks of pollution, disease, and other hazards. This process makes the healthcare sector a major contributor to environmental problems, particularly due to its high carbon emissions (Zikhathile et al., 2022). The healthcare industry generates various types of waste, such as solid wastes (trash, garbage, or municipal solid waste), biohazardous wastes (sharps, human blood, etc.), hazardous chemical wastes, and medical wastes (wastes are generated at healthcare facilities) (Azmal et al., 2014). Another classification includes infectious, chemical, sharps, pathological, cytotoxic, pharmaceutical, and radioactive wastes (Zikhathile et al., 2022). Disposal of wastes produces both high financial costs and environmental problems. Traditional disposal approaches or treatment technologies such as incineration, microwave irradiation, or chemical methods cannot be the best solution due to secondary environmental problems, high costs, limits, and/or high diversity of healthcare wastes (Zikhathile et al., 2022). Transforming hospitals and other medical facilities, as generators of major healthcare wastes, to

Table 1: Examples of green applications in selected technology fields

Technology Field	Green Applications	Impacts
Nanotechnologies	building materials - recyclable and long-lasting concrete - steel - insulation materials protective surface applications - low-e coatings - UV protection - solar protection - dynamic glazing self-cleaning coatings applications - self-cleaning paints - easy-to-clean surfaces temperature regulation applications, insulation applications - insulating paint and panels energy storage applications - electrical energy from a paper battery energy generation applications - solar glass, and semiconductor devices	Green nanotechnology applications are frequently used to minimize energy demand in buildings, which account for about 40% of global energy demand. They reduce energy demand for heating, cooling, and lighting, decrease environmental pollution by minimizing energy losses, and lower carbon emissions (CO ₂) by extending the lifespan of materials. Additionally, nanoparticles used in water and groundwater treatment can be accepted as other green nanotechnology applications. They reduce secondary pollution caused by traditional chemical applications. Finally, they can be used in energy generation and storage processes to increase efficiency. Therefore, green nanotechnologies are environmentally friendly, as they increase energy efficiency and reduce energy demand. They decrease carbon emissions.
Biotechnologies and Pharmaceutical Technologies	waste-reducing biotechnologies - applications (e.g., using microalgae for wastewater treatment) that convert food waste into biofuel or animal feed biological wastewater treatment - applications (e.g., MABR (Membrane Aerated Biofilm Reactor) Treatment), reducing water pollution plant or agricultural biotechnologies - genetic modification or editing of drugs green chemical applications - applications (e.g., sonochemical approach) that reduce waste and the use of materials in the production of drugs	Green biotechnology and pharmaceutical applications are frequently used, especially to reduce and purify waste from the food, agriculture, and pharmaceutical sectors, which are primarily responsible for carbon emissions. Therefore, green biotechnologies are environmentally friendly applications as they reduce production costs and increase productivity. They also ensure the protection of biodiversity.
Medical Technologies	green medical materials - mercury-free products - non-polyolefin intravenous bags - installing mercury traps green medical waste management methods - utilization of solar treatment methods in Healthcare Risk Waste Treatment (HCRW)	Green medical technology applications are frequently encountered, especially in reducing biohazardous and chemical hazardous waste generated by medical products and procedures in the health sector. On the other hand, designing and managing hospitals to create less waste is also an example of green medical technology applications. They mitigate the environmental impacts of medical products and procedures and offer financial benefits. Given that the healthcare industry is the second-largest waste-generating sector in almost all countries, these applications can be considered environmentally friendly.
ICTs	smart ICTs - supply chain and logistics optimization intelligent - communication, and e-commerce - traffic management systems (ITMS) - building management systems (BMS) - ICT-driven automation - smart grids in the renewable energy sector	Green ICT applications are widely used across many sectors, including energy, construction, transportation, trade, automotive, and more, to reduce carbon emissions. Indeed, the digital transition is related to the green transition. For this reason, they are called the twin transition. As the digital transition based on ICTs is implemented across production and consumption processes, the economy will become greener.

Source: Compiled by authors from various sources

adapt green or environmentally-friendly practices that reduces wastes has become a significant issue today. Green medical materials and medical waste management methods could mitigate the healthcare industry's impact on climate change. However, while the increase in green medical technologies has the potential to spread through knowledge spillovers, their impact may remain

limited due to the slow pace of green transition within the healthcare sector.

The concepts of green **ICTs**, green/ecological informatics, or green computing have gained popularity, particularly over the last decade, due to the increasing negative environmental impacts of ICTs, driven by non-renewable

energy sources and non-degradable waste from the widespread use of ICT products (Radu, 2014). Green ICTs include ICT tools, products, services, and technologies, in combination with green practices or behaviors, that can reduce energy consumption and provide monitoring and control systems to protect the ecosystem (Zacharoula, 2012). Additionally, smart ICTs, particularly those used in energy generation, storage, and distribution, as well as in the building and transportation industries, can help reduce CO₂ emissions. These technologies focus on the development and use of environmentally-friendly ICT products. According to a GeSI report, ICTs have the potential to reduce global carbon emissions by a factor of five times their own carbon footprint (Roeth and Wokeck, 2011). Therefore, ICT-based or ICT-enabled green methods, referred to as green ICT or green informatics, such as measuring, monitoring, and managing processes across industries, can reduce carbon emissions and mitigate climate change impacts on the environment. Examples include intelligent traffic management systems (ITMS), supply chain and logistics optimization, (M2M) communication, and e-commerce in logistic sector; remote management systems and building management systems (BMS) in buildings sector; smart grids, advanced process control (APC), and ICT-driven automation of industrial process; and in integration of renewable energy industry sector (Roeth and Wokeck, 2011). As the share of green informatics or green ICTs increases, information and communication technologies can expand through knowledge spillovers. In other words, as the green dimension of ICTs grows, their overall use and impact can develop as well.

Based on the above discussion, the study hypothesizes that there is a statistically significant short-run and long-run linkage between green technologies and several key fields, including biotechnology, medical technology, nanotechnology, pharmaceutical technology, and information and communication technology (ICT).

Establishing the statistical significance of this relationship would not only support the interconnectedness of these technology sectors but also provide evidence that advancements in green technologies contribute to broader innovations in these fields.

If a strong relationship is confirmed, it could indicate that integrating green technologies into these areas is a crucial step toward facilitating a green transition. This transition is critical for meeting environmental challenges and supporting sustainable development. Thus, demonstrating this relationship may serve as a valuable indicator of progress towards a more sustainable, eco-friendly technological landscape.

ECONOMETRIC ANALYSIS

In the literature, knowledge spillovers are estimated using relationships between knowledge and macroeconomic indicators such as economic growth and exports (Guo et al., 2020; Jiao et al., 2020). However, a more precise estimation of knowledge spillovers should focus on the impacts of existing knowledge on new knowledge (Barbieri et al., 2020; Nie et al., 2021), aligning with the definition of knowledge spillovers. In this study, green knowledge spillovers are elicited by exploring the relationship between patent registrations in green technologies and those in the selected technology fields using the ARDL Model. This approach allows the ARDL Model to capture knowledge spillovers from green technologies to other selected technology fields both in the short-run and long-run. Moreover, the ARDL Model captures a cyclical cumulative effect of knowledge through the inclusion of lagged values of dependent and independent variables.

Knowledge spillovers are analyzed in the empirical literature using different estimation methods and econometric models such as dynamic panel models

Table 2: Variables (1988 to 2020)

<i>Variables</i>	<i>Symbols</i>	<i>Explanations</i>	<i>Expected Signs</i>	<i>Sources</i>
<i>Dependent Variables</i>	BIO _{TECHS}	The number of patent registrations in biotechnology		OECD.stat
	MED _{TECHS}	The number of patent registrations in medical technologies		
	PHARMA _{TECH}	The number of patent registrations in pharmaceuticals t		
	NANO _{TEHCS}	The number of patent registrations in nanotechnology		
	ICT _{TEHCS}	The number of patent registrations in ICT		
<i>Independent Variable</i>	GREEN _{TECHS}	The number of patent registrations in environment-related technologies (green technologies)	+	

(Yao, 2006) and spatial econometric models (Fischer and Varga, 2003; Feng and Yuan, 2025) as well as traditional panel models. In addition, several studies focus on Logit Models (Maurseth and Verspagen, 2002). Finally, there are also studies that analyze knowledge spillovers through cointegration models (Seck, 2012; Adedoyin et al, 2022; Dzwigol et al., 2023) as in this study.

DATA

The data encompass patent applications taken from the OECD database. The dependent variable is the number of patent applications in OECD selected technological fields, and the independent variable is the number of patent applications in green technologies during the period between 1988 and 2020. Table 2 presents the variables and their explanations¹.

METHOD

The ARDL model is used to investigate variables that are stationary at different levels empirically. Together, these methodologies provide a robust framework for analyzing the dynamic relationships among variables in the presence of non-stationarity and structural changes. The ARDL model is a suitable methodology for the econometric analysis of variables with different stationary levels due to its more flexible conditions (Pesaran et al., 2001). Furthermore, the ARDL is more efficient in small and finite samples, and it provides unbiased coefficients relatively (Harris and Sollis, 2003). Accordingly, the ARDL model can be specified as in Eq. (1).

$$Y_t = \gamma_{0i} + \sum_{i=1}^p \delta_i Y_{t-i} + \sum_{i=1}^q \beta'_i X_{t-i} + \varepsilon_{it} \quad (1)$$

Here, Y_t and X_t are vectors of dependent and independent variables, respectively, which can be $I(0)$, $I(1)$, or cointegrated. γ_{0i} and β'_i are coefficients, γ_{0i} is a constant term, and p and q represent optimal lag orders determined by Akaike Information Criteria. ε_{it} is a vector of error terms. Firstly, the long-run relation among variables should be tested using ARDL Bounds Test, whose null hypothesis states that no level relationship for cointegration exists and it is specified in Eq. (2). If the F-statistic value exceeds the $I(1)$ the null hypothesis is rejected while if it remains below $I(0)$, the null hypothesis is accepted (Sikder et al., 2022). In other words, rejecting the null hypothesis refers to the long-run relationship or long-run knowledge

spillovers from green technologies to other selected technology fields.

$$\Delta Y_t = \gamma_{01} + \delta_1 Y_{t-1} + \beta_1 X_{1,t-1} + \sum_{i=1}^p \delta_{2,i} \Delta Y_{t-i} + \sum_{i=1}^q \beta_{2,i} \Delta X_{t-i} + \varepsilon_{it} \quad (2)$$

The short-run relationship among variables can be analyzed using the ARDL Error Correction Model (ECM), which can be specified as in Eq. (3).

$$\Delta Y_t = \gamma_{01} + \sum_{i=1}^p \alpha_{1,i} \Delta Y_{t-i} + \sum_{i=1}^q \alpha_{2,i} \Delta X_{t-i} + \phi ECT_{t-1} + \varepsilon_{it} \quad (3)$$

Here, ϕ refers to the speed of adjustment, which must have a negative sign. ECT refers to the error correction term, which determines the speed of adjustment for the long-run equilibrium. and These are the short-run coefficients. Their significances indicate the short-run relationship between green technologies and other selected technology fields.

EMPIRICAL FINDINGS

Table 3 shows the results of traditional unit root tests, which are Augmented Dicky Fuller (ADF) and Phillips-Perron (PP), for comparison. The variables became stationary at different levels, as indicated by their $Z(\rho)$ and $Z(t)$ statistics at the 5% significance level. Specifically, $Z(\rho)$ and $Z(t)$ statistics of $GREEN_{TECHS}$, BIO_{TECHS} , MED_{TECHS} , and ICT_{TECHS} variables exceed ADF and PP Test's critical values at the 5% level, indicating that they are stationary in first difference. In other words, they are stationary at $I(1)$. In contrast, the $Z(t)$ statistic for the level of the $NANOTECHS$ variable exceeds the critical value, meaning that it is stationary at $I(1)$.

According to ARDL Bounds Test's findings shown in Table 4, a long run cointegration relationship is observed only for $NANOTECHS$, not for $BIOTECHS$, $MEDTECHS$, $PHARMATECHS$, and ICT_{TECHS} . This indicates green technologies are associated only with nano-technologies in the long run. In other words, there are long-run knowledge spillovers from green technologies to nano-technologies, which is consistent with the findings of Aldieri et al. (2019) and Barbieri et al. (2020).

Table 5 presents the ARDL long-run and short-run coefficients for all variables. However, the long-run coefficients of the relationship between $GREEN_{TECHS}$ and $NANO_{TECHS}$ can only be interpreted. Because there is no long-run relationship between green technologies and other technology fields. Accordingly, the long-run results indicate a positive and significant long-run relationship between $NANO_{TECHS}$ and $GREEN_{TECHS}$. Specifically, a 10% increase in the number of patent registrations in $GREEN_{TECHS}$ is related to 5.7% increase in patent registrations of $NANO_{TECHS}$ in the long run.

¹ The study examined the knowledge spillovers through the patent relationship. The factors that could be simultaneously affect technological developments such as R&D expenditures and international collaborations are ignored due to the potential multicollinearity problem in the empirical analysis.

Table 3: Unit Root Tests Structural Break (with / without)

Variables	Augmented Dickey Fuller (C+T)	Phillips Perron (C+T)	
	Z(t)	Z(rho)	Z(t)
GREEN _{TECHS}	-0.338	-0.129 (3)	-0.103 (3)
D.GREEN_{TECHS}	-6.439*	-32.701* (3)	-6.645* (3)
BIO _{TECHS}	-0.732	-0.266 (3)	-0.092 (3)
D.BIO_{TECHS}	-8.322*	39.058* (3)	-9.263* (3)
MED _{TECHS}	-0.832	-0.517 (3)	-0.416 (3)
D.MED_{TECHS}	-7.147*	-30.047* (3)	-9.170* (0)
PHARMA _{TECHS}	-0.258	-0.199 (3)	-0.118 (3)
D.PHARMA	-6.434*	-35.724* (3)	-6.448* (3)
NANO_{TECHS}	-2.067*	-7.134 (3)	-1.845 (3)
D. NANO_{TECHS}	-6.859*	-30.231* (3)	-8.051* (0)
ICT _{TECHS}	-0.789	-0.882 (3)	-0.560 (3)
D.ICT_{TECHS}	-8.320*	-43.840* (3)	-8.300* (3)
Augmented Dicky Fuller Critical Values (%5)		Z(t): -1.950	
Phillips Perron Critical Values (%5)		Z(rho): -12.660 Z(t): -2.986	

Note: Values in parentheses refer to the lag values determined by Akaike Information Criteria (AIC). * refers %5 significance level. C+T refers values with constant and trend. In the table, unit root tests' values with intercept and trend were supplied since all variables contain trend.

Table 4: Pesaran-Shin-Smith (2001) ARDL Bounds Test

	Model 1 BIO _{TECHS}		Model 2 MED _{TECHS}		Model 3 PHARMA _{TECHS}		Model 4 NANO _{TECHS}		Model 5 ICT _{TECHS}	
<i>F-stat</i>	3.180		0.379		2.146		7.760		2.611	
	<i>I(0)</i>	<i>I(1)</i>	<i>I(0)</i>	<i>I(1)</i>	<i>I(0)</i>	<i>I(1)</i>	<i>I(0)</i>	<i>I(1)</i>	<i>I(0)</i>	<i>I(1)</i>
%1	6.84	7.84	6.84	7.84	6.84	7.84	6.84	7.84	6.84	7.84
%5	4.94	5.73	4.94	5.73	4.94	5.73	4.94	5.73	4.94	5.73
	No		No		No		Yes		No	
H ₀ : no levels relationship										

In the short run, positive and statistically significant relationships are observed between GREEN_{TECHS} and other technological fields, except for medical technology. This suggests that green technologies do not have a statistically significant relationship with medical technologies, either in the short run or the long run. However, green technologies have a positive and statistically significant impact on biotechnology, pharmaceutical technology, nanotechnology, and ICT. A 10% increase in patent registrations for green technologies is associated with respective increases of 3.5%, 3.8%, 4.6%, and 4.3% respectively, in biotechnology, pharmaceutical technology, nanotechnology, and ICT patent registrations in the short run.

The results indicate that the most significant positive short-run impact of green technologies is observed in the nanotechnology sector, followed by ICT, pharmaceutical technology and biotechnology. This suggests that the effects of green transition processes are beginning to emerge in ICT, pharmaceutical, and biotechnologies fields, but they remain insufficient. In contrast, the statistically insignificant short- and long-run green knowledge spillovers in the medical technology sector indicate a lack of green transition within Türkiye's medical industry. Finally, consistent with Shengrong and Liandwen (2019), there is a cyclic cumulative effect in the selected technology fields except for the nano-technology field.

Table 5: ARDL Long-Run Coefficients

	Model 1 ARDL (1, 0) y: BIO _{TECHS}	Model 2 ARDL (3, 0) y: MED _{TECHS}	Model 3 ARDL (1, 0) y: PHARMA _{TECHS}	Model 4 ARDL (1, 0) y: NANO_{TECHS}	Model 5 ARDL (1, 0) y: ICT _{TECHS}
ADJ					
y	-0.34** (0.1497)	-0.14 (0.1882)	-0.31** (0.1554)	-0.80*** (0.2048)	-0.36** (0.1608)
L1.					
LR					
GREEN _{TECHS}	1.008*** (0.2126)	1.10** (0.4597)	1.21*** (0.2225)	0.57*** (0.1074)	1.17*** (0.2275)
cons.	-0.021 (0.2083)	0.35** (0.1721)	0.025 (0.1982)	-0.66** (0.3147)	0.20 (0.2252)
Root MSE	0.59	0.51	0.61	0.75	0.73
Adj-R ²	0.13	0.28	0.07	0.32	0.10
ARDL (p, q) Regression Results					
	Model 1 ARDL (1, 0) y: BIO _{TECHS}	Model 2 ARDL (3, 0) y: MED _{TECHS}	Model 3 ARDL (1, 0) y: PHARMA _{TECHS}	Model 4 ARDL (1, 0) y: NANO _{TECHS}	Model 5 ARDL (1, 0) y: ICT _{TECHS}
y					
L1.	0.65*** (0.1497)	0.49** (0.1956)	0.68*** (0.1554)	0.19 (0.2048)	0.63*** (0.1608)
L2.		-0.18 (0.2038)			
L3.		0.53*** (0.1724)			
GREEN _{TECHS}	0.35** (0.1402)	0.16 (0.1874)	0.38* (0.1926)	0.46*** (0.1512)	0.43** (0.2107)
cons.	-0.21	0.35**	0.02	-0.6**	0.20
Adj-R ²	0.86	0.92	0.91	0.61	0.88
Breusch-Godfrey LM Test	2.358 [0.1247]	0.440 [0.5069]	0.611 [0.4345]	0.588 [0.4433]	2.607 [0.1064]
White's Test	15.53 [0.0083]	23.06 [0.0594]	10.83 [0.0548]	3.10 [0.6840]	18.10 [0.0028]
JB Normality Test	1.578 [0.4543]	2.216 [0.3301]	1.102 [0.5763]	2.567 [0.2770]	2.549 [0.2796]

Note: *, **, *** stands for, respectively, %10, %5 and %1 significance level, statistics in parentheses () stands for standard errors; statistics in square parentheses [] stands for p-values.

CONCLUSION

A long-run relationship in terms of knowledge spillovers exists between green technologies and nanotechnologies according to the findings of the ARDL Model. This result could be largely associated with nanotechnology registrations in the construction sector, which has been popularized with urban transformation policy. Additionally, in the short run, green technologies have positive and statistically significant spillover effects on biotechnology, pharmaceutical, nanotechnology, and ICT areas. This indicates the impacts of green transition are beginning to emerge in these fields.

The statistically insignificant short-run and long-run green knowledge spillovers in the medical technology sector suggest a lack of green transition in the health industry in Türkiye.

It shows that green technologies do not have a statistically significant relationship with medical technologies, either in the short run or the long run. Present healthcare waste treatment technologies may be inadequate in reducing the negative environmental impacts of the healthcare industry (Zikhathile et al. 2022). Policymakers should prioritize green transition of healthcare system and hospitals, which are major

sources healthcare wastes. Ensuring green transition in the health sector should become a key policy issue in Türkiye. For example, the incentive system should be revised to prioritize green transition in the healthcare. Reducing the environmental effects of healthcare products can be achieved both by upstream activities (e.g. purchasing mercury-free products to reduce mercury emission or using non-polyolefin intravenous bags instead of polyolefin intravenous bags containing polyvinyl chloride to decrease dioxins through incineration) and downstream strategies (e.g. installing mercury traps in drains to reduce mercury emissions) (Kaiser et al., 2001). Additionally, green technologies in water and solid treatment, and air purification can play a critical role in reducing biomedical waste (Sindhu et al., 2021). Financial incentives should focus on upstream activities, downstream strategies, and water and solid waste treatment. However, the progress of this transition has been slow due to patient safety concerns or misunderstandings, such as misconceptions about efficacy, cost concerns, implementation complexity, and regulatory and compliance issues (Kwakye et al., 2010).

Based on the research findings, several key policy implications emerge to guide the effective implementation of green technologies and sustainable practices across various sectors in Türkiye.

Focus on Greener Healthcare: The green transition should be supported in the healthcare sector, which has serious deficiencies in terms of green practices. In both the short and long run, there is no statistically significant relationship between green and medical technologies. In this regard, sectoral policies should be directed towards green medical technologies, including effective waste management strategies and the production of greener medical products. Emphasizing these changes can help reduce the environmental impact of healthcare operations while maintaining patient safety.

Integrate Green and Digital Transitions: According to the empirical findings, the effects of green transition processes are beginning to emerge in ICT, but they remain insufficient. Therefore, urban transformation policies should integrate both green and digital technologies, as they are mutually dependent. Policymakers should ensure that the two fields work together to achieve the best results.

Foster Collaboration and Innovation: Encouraging collaboration between government, industry, universities, and research centers can be a helpful strategy for the adoption of green technologies. Thanks

to this collaborative environment, green ideas can be combined with green practices.

By implementing these policy measures, green transition efforts can be advanced in parallel to the Sustainable Development Goals. The aim is to enhance the overall effectiveness of urban transformation initiatives.

The findings offer valuable insights into the current state of green transition efforts across sectors. They enable comparison of the green transition success level of sectors. To build on these insights and drive continuous improvement, it is crucial to address several key areas through further research, including understanding the short- and long-run impacts, the implementation barriers, and the effectiveness of different policies to refine strategies and enhance the overall effectiveness of green transition initiatives.

Future research should focus on exploring the long-term impacts of green technologies, particularly in the healthcare sector, to understand their sustained benefits and challenges. In addition, the effectiveness of financial incentives and support mechanisms in the green transition process of selected industries should be investigated. Finally, the effects of technological developments in the selected technology fields on green technologies should be further investigated.

Declaration of generative AI and AI-assisted technologies in the writing process

In the study, ChatGPT and Grammarly were used to improve the language of the manuscript.

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