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Research article

Implications of circular economy, digitalization and technological innovation to achieve sustainable environmental goal: Pre and post-vision 2030

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A R T I C L E I N F O

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A B S T R A C T

The current study contributes to the existing literature by constructing a digitalization index to investigate the significance of digitalization in controlling the environmental footprint. Moreover, the dataset is divided into pre-Vision 2030 and post-Vision 2030 implementation to scrutinize the progress of Saudi Vision 2030 to counter the environmental challenges. Vision 2030 is a strategic framework to reduce Saudi Arabia's dependence on oil, diversify its economy, and develop public service sectors such as health, education, infrastructure, recreation, and tourism. The findings have documented the negative coefficients for post-Vision 2030 and post-COVID-19 estimations, reflecting that a significant digitalization increase is useful for controlling the environmental externalities in Saudi Arabia. In the case of post-Vision 2030, the role of environmental technology turns out to be significant and negative, but with a lower magnitude. The study results are useful for drawing significant environmental policies through enhancing the digitalization parameters and advancement of technology.

1. Introduction

Recently, in the past, the factors influencing the environment and its degradation have instantly emerged, which has shaped and molded severe threats to environmentally friendly goals and policy decisions. Recently, the counterpart of the Paris Agreement has engaged COP27 in Egypt to reaffirm the environmental efforts that will be useful to decrease the global temperature by 1.5 °C. Therefore, to achieve these goals, ecological footprints are under the concertation of governments and academia [1]. The ecological stress of humankind on the planet calculated by ecological footprint has been engorged, which upsurges ecological threats. The concept was initiated by Ref. [2], hence defined ecological footprints as the total area of naturally productive land required to generate the resources reduced by population or ability to absorb waste. It comprehends the ecological standard and the law of the environmental economy, protects resources, and eradicates or diminishes the pressure on the environment. It estimates the influence of

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individuals on the networks by gauging the number of environmental sources used by human beings for their well-being. It has been seen that nature requires environmentally friendly policies; therefore, green energy technology is an imperative promoting factor of ecological footprints.

Another point of concern, led by the industrial revolution, stated that the world economy had joined Another point of concern, led by the industrial revolution, stated that the world economy had joined an era of speedy development, and the space concerning the level of the rich and the poor had broadened. The growth of the economy also produces the environmental pollution dilemma, which threatens the endurance of human beings. Thus [3], stated that digital technologies fundamentally reshape the worldwide economic system and are a transformational mechanism that helps achieve social, financial, and environmental consequences by interpreting sustainable business strategies into everyday operations. Furthermore, new technologies are significant for stimulating ecological morals at the organizational intensity while augmenting a firm's effectiveness. However, the world is facing a hazard to the environment by digitalization. According to Ref. [4], the carbon footprint generated by the digital sector accounts for 2.1 and 3.9 % of global emissions in 2020. People are unaware of the streaming technologies' ecological footprints; Online video watching signifies the largest portion of global internet traffic at 60 %. Increasing mobile usage can relieve about 40 percent of carbon emissions in the global industrial, top emitters in the next ten years [5]. In addition, according to a report by GSMA 2023, digitalization is considered a vital enabler of the de-carbonization evolution. It can facilitate the production, power sector, transportation, and civil sectors to condense their carbon footprint. Thus, the importance of the digital sector in the rapid and massive reduction of ecological footprint is defined by the Paris Agreement as the digital sector is contingent on several other sectors such as energy, mining, and logistics, hence, a risk to other developmental sectors.

The study incorporates Saudi Arabia because ever since it participated in Vision 2030, the economy has evolved as a rapid global technology development and government and institutional trends. It has substituted traditional methods with digital ones, emerging five-year plans to attain quality and competence. Saudi Arabia has significantly benefited from its digital transformation program in recent years, resulting in a healthier experience for its inhabitants and tourists, as well as more well-organized public services. The aim is to digitally revolutionize the government's services to make it easier. The program of Saudi Arabia, in the first phase (2016–2020), contributed to many central endeavors, including intensifying digital transformation and technology solutions. Whereas, the government has decided to enhance the digital transformation and aimed to reach over 60 fintech startups and has seen tremendous growth in the Internet of Things (IoT), reaching over 10 million networks [6]. The overarching objective of Vision 2030 is to segregate away from oil and construct a digitalized, knowledge-based economy, and the population optimistically welcomes these opportunities that more digitization will create for them. In a survey, 79 % of respondents trust that improvements in technology will progress their future job scenarios, and nearly 90 % assured that they can acclimate the new technology usage into their workplaces.

This study enhances the literature on environmental health economics from various angles. First, this work constitutes the digitalization index for Saudi Arabia to examine the role of digital on the environmental footprint. The reason to address the effect of Information technology on the ecological footprints (EFP) in the Kingdom of Saudi Arabia (KSA) is because literature is exceedingly rare. The digital sector is supported by its ability to use fewer resources competently. Due to the lack of literature, it's important to address the impact of information technology on ecological footprints (EPI) in the Kingdom of Saudi Arabia (KSA). In addition, transportation can be utilized more efficiently. The key contribution in this context is to construct the digitalization index for the case of Saudi Arabia, which is quite important to magnify the role of digitalization on ecological footprint. Previous studies, in context of Saudi Arabia, have emphasized on the formation of environmental index, economy index etc. whereas, the current study apply the digitalization index. Instead of choosing one digitalization indicator, the use of index encompasses the broad perspective by including the number of digitalization proxies which provides the in dept analysis. Secondly, examine the role of technological indicators on the environment in Saudi Arabia. For this purpose, we have incorporated two proxies of technology; technological advancement and environmental technology. It is important in the case of Saudi Arabia, as the oil-dependent country is strongly linked with several environmental hazards, and previous literature sturdily supports the relationship of green innovation and technology and ecological footprints [7–9]. Thirdly, it examines the role of digitalization and technology indicators in view of Vision 2030. For this purpose, the research simulated the dataset to 2020 by using the Markov chain Monte Carlo (MCMC) algorithm and converted it to the monthly dataset, as follows by Refs. [10,11]. The absence of extensive studies addressing the relationship between digitalization, technology, and ecological footprints in the case of Saudi Arabia, therefore, motivates to improve understanding in this context. Consequently, this study explores the relationship of the KSA from 1998 to 2022 by using the non-linear ARDL technique.

Fourthly, another important contribution is the findings of COVID-19 estimations, which impact ecological footprints due to a lack of economic activities and lockdown restrictions. The Kingdom of Saudi Arabia (KSA) acted as the second largest country to take part in preventive measures to control the COVID-19 pandemic and also witnessed a reduction in NO_2 in the post-COVID-19 atmospheric situation by the country [12]. The importance of this pandemic is an enabler in observing the impact on ecological footprints. In addition, the research offers significant policy implications for scholars and decision-makers who may need the requisite clarification for digitalization and technology to address environmental difficulties.

The study has multiple objectives: Firstly, the recent paper analyzes economic growth's role in alleviating environmental externalities. Secondly, it identifies the influence of digitalization on environmental degradation. Thirdly, the study indicates the technological indicators expediency to control environmental degradation. Lastly, the research investigates the importance of Saudi Vision 2030 and its impact on countering the environmental challenges in Saudi Arabia.

A literature review leads to the formation of a hypothesis. It is hypothesized that economic growth, digitalization, and technological indicators significantly affect the ecological footprint of Saudi Arabia. Results show that digitalization and technological indicators reduce ecological footprint. However, economic growth enhances the ecological footprint. The paper is segmented into a literature review followed by a data and variables description. The latter segment provides the methodology used in the study. The next part gives the results and discussion, and in the last, the conclusion and recommendation of the research work.

2. Literature review

Over the last decades, a huge quantity of literature has concentrated on the relationship between economic growth, technological factors, and the degradation of the environment. However, there is an absence of literature involving digitalization and ecological footprints. In this segment, the research discusses the prevailing literature to evaluate the relationship between all the selected variables and ecological footprints.

Several types of research found a relationship between ecological footprints and economic growth, such as a positive relationship between ecological footprints and economic growth [7,9]. According to Ref. [13], economic growth is the highest contributor to increasing environmental hazards in Saudi Arabia. Similarly [14], selected the USA, Russia, Saudi Arabia, Canada, China, Brazil, Kuwait, and Nigeria and declared a positive relationship between economic growth and ecological footprints. In contrast to these researches [15], found a mixed relationship that all selected countries spur emissions by economic growth except the Dominican Republic. However the majority describe its negative impact on the environment [16]. states that the impact of economic growth on ecological footprints fluctuates based on income level. The research concludes that the magnitude becomes smaller at higher quantile levels than at lower quantiles. The study by Ref. [17] explored a significant and inverted U-shaped association between economic progress and ecological footprints. As far as short-run concern [18], concluded that economic growth causes an increase in emissions.

Several studies describe a negative relationship between digitalization in the form of digital economic activities, digital technologies, or the digital sector [19–22]. gives the observation that digitalization decreases the ecological footprints in the country. Similarly, there is a view of hazards to the environment by digitalization, such as [23,24], concerned by the results that digital activities increase carbon emissions [25,26]. found no significant impact on environmental health by increasing digital activities. An additional important view of the inverted U-shaped relationship between digitalization and ecological footprints is declared by Refs. [27,28] proposes that the increasing trend at the beginning of the digital economy improvement but deteriorations in the later stage because of some regional differences.

The study constitutes two variables referring to technological advancement and environmental-related technologies [29]. evaluated innovation's effect on Pakistan's environmental worth between 1971 and 2016. Researchers found that technology has a beneficial influence on CO2 [30]. established a negative relationship between technological innovation and ecological footprints [31]. also found a negative relationship between technology level and ecological footprints [32]. is of the view that technological innovation successfully decreases carbon emissions but does not significantly affect the ecological footprint [33]. studied in Kazakhstan from 1992 to 2014 and declared positive relationships between ecological footprints and technology.

Environmental technologies aid in decreasing ecological footprints, as earlier research proved [9]. using regional data of China from 2000 to 2019, by opting for Quantile Autoregressive Distributive Lag (QARDL), indicated that green technology innovation assists in reducing ecological footprints. In the short run, the results confirm that environmental technologies support the environment. Another research by Ref. [7] explored the relationship between ecological footprints and green innovation in the top 20 green innovators countries. From 1993 to 2016, they found that these countries depicted significant negative effects of environment-related technologies on ecological footprints. Thus, increasing green innovation is subject to a decrease in ecological footprints [16]. found the same results in the case of 38 countries which belongs from "Organization for Economic Co-operation and Development" and "Brazil, Russia, India, China, and South Africa" (OECD + BRICS countries) [34]. analyzed environmental technologies for the period of 1982–2016 across 35 countries. A method of panel regression analysis exposed that environmental technologies improve the ecological footprint, the same as [35]. A zero-impact relationship between environmental-related technologies and ecological footprint is rare and is dependable on sector or industries, such as [36] unveil that environment-related technological innovation has no reliable potential to elucidate the deviation in CO_2 emissions only in the case of the transportation sector. At the same time, solar energy is observed to impact the environment positively in the long run.

The highlight of the literature is multifold; a large number of studies have investigated the role of digitalization and technology on the environment. However, according to the provided literature, none of the studies have constructed the digitalization index to rectify the role of the digitalization index on the environmental footprint in Saudi Arabia. The current study formulates the digitalization index, a combination of secondary and sub-categories of digitalization indicators to fill this gap. Instead of focusing on one or two digitalization proxies, the digitalization index is useful for providing detailed insight into the relationship between digitalization and the environmental footprint in Saudi Arabia.

3. Data and methodology

The research constitutes Saudi Arabia's annual time series data from 1998 to 2022. Where the data for 2021 and 2022 are simulated by using Markov chain Monte Carlo (MCMC) algorithm. Due to a lack of observations, the data has been converted into a quarterly basis. For the simulation and data transformation, the research followed [37]. According to the world economic forum, the Saudi Arabian government has built communities and lifted the economy by redeveloping the digital infrastructure. The country has capitalized in research and innovation sectors with an annual investment of 2.5 % by 2040. Thus, the innovative sector contributes to modern technologies, and the country aims to increase the GDP by $16 billion and transform energy and resources to make a better place to live, visit and invest.

In earlier research, carbon emissions were considered accurate for evaluating environmental quality, but as time passed, modern ideas by researchers gained interest in representing and measuring ecological worth. Carbon, PM2.5, Sulphur oxide (SO_2), ozone (O_3), carbon monoxide (CO), and many more have been used as proxies to represent the environment [12,38,39]. However, this research supports the idea of an ecological footprint that measures resources consumed by individuals and their ability to regenerate for further usage [2]. discovers that, among other factors, it also deals with urbanized land resource consumption, and scholars have proved that economic progress, digitalization, and technologies have a direct association with urbanization such as [40–42]. The study incorporated a digitalization index which is constructed for econometric analysis.

Furthermore, the paper incorporates technological factors such as technological advancement associated with innovation in the country and environmental technology development to use green resources for further economic progress. The study used countries' and firms' innovative performance and design policies to represent technological advancement [43] and the development of environment-related technologies; the percentage of all technologies is a proxy for environmental technology [16]. Economic growth has been taken as control variables proxies by GDP. GDP is defined as the production undertakings of all local resident divisions in a particular period and is the essential point of national economic accounting depicting the country's economic condition and progression level [42].

3.1. Construction of digitalization index (DI)

In comparing previous studies, this study forms the digitalization index to examine the impact of digitalization on environmental footprint. Whereas, the previous studies pick one of the digitalization indicators, which is not an appropriate approach to evaluate the overall significance of environmental indicators. Despite the previous digital index, the researchers have diverse opinions about the pros and cons of these indicators. However, we construct a new digitalization index that covers four secondary indexes, (i) digital infrastructure, (ii) digital economy, (iii) digital industry, and (iv) digital applications.

Digital infrastructure is about the internet indicators, constituted of three sub-indicators. The first sub-index is individuals using the internet (% of the population), reflecting internet penetration. The second indicator is mobile penetration, which uses the data of mobile cellular subscriptions (per 100 people). Thirdly, we use the number of fixed broadband subscriptions in Saudi Arabia (in millions).

For the digital economy, we employ three sub-indicators; firstly, industry revenue of information service activities in Saudi Arabia (in million US Dollars) represents the performance of the information industry. Secondly, industry revenue of computer programming, consultancy and related activities (in million US Dollars) are considered. Thirdly, fixed and data telecom sector revenues (in billion US dollars) are used. The revenues of all these digital and information sectors represent digital revenue.

The third category concerns the digital industry, which focuses on three sub-categories. The first one is the value of total online retail in Saudi Arabia (in million US dollars). The second is about the number of online shoppers in Saudi Arabia (in millions). Third is the high-technology exports (in percentage). The fourth category deals with digital applications, which aims to scrutinize the applicability of digital platforms in commerce and retail. For this purpose, we have used three sub-categories of digital applications; first, market size of smart entertainment control systems for homes in Saudi Arabia (in million US dollars). The second is about e-commerce market size in Saudi Arabia (in billion US dollars) and third is retail internet of things (IoT) spending. To address the missing data, we have used interpolation and extrapolation methods. Table 1 represents the secondary and sub-categories of the digitalization index (DI).

Table 2 presents complete information on the selected variables and the measuring details. The study constructs two models by involving the selected variables. Model 1 addresses the environment through the use of digitalization and economic growth. Equation (1) represents the economic form of the model. Whereas, Equation (2) presents the econometric form of the model which will be used for econometric analysis.

$$EFP = f\ (DI, GDP) \tag{1}$$

$$lnEFP_t = \alpha_0 + \beta_1\ lnDI_t + \beta_2\ lnGDP_t + \varepsilon_t \tag{2}$$

Model 2 is the extension of model 1 which includes the digitalization, economic growth, technology and environmental technology.

Table 1
Mechanism of digitalization index (DI).

Digitalization Index	Secondary Index	Sub—category
Digitalization Index (DI)	Digital infrastructure	Individuals using the internet (% of population)
		Mobile cellular subscriptions (per 100 people)
		Number of fixed broadband subscriptions in Saudi Arabia (in millions)
	Digital economy	Industry revenue of "information service activities "in Saudi Arabia (in million U.S. Dollars)
		Industry revenue of "computer programming, consultancy and related activities " (in million U.S. Dollars)
		Fixed and data telecom sector revenues (in billion U.S. dollars)
	Digital industry	Value of total online retail in Saudi Arabia (in million U.S. dollars)
		Number of online shoppers in Saudi Arabia (in millions)
		High-technology exports (%)
	Digital application	Market size of smart entertainment control systems for homes in Saudi Arabia (in million U.S. dollars)
		E-commerce market size in Saudi Arabia (in billion U.S. dollars)
		Retail IoT spending

Table 2
Sources of studied variables.

Notation		Proxy	Source
Dependent variable			
EFP	Environmental footprint	Environmental footprint	Global Footprint Network (GFN)
Digitalization			
DI	Digitalization index	Digitalization index	Author formulation
Control Variable			
GDP	Economic growth	GDP current US dollar	World Development Indicators (WDI)
Technology			
TECH	Technological advancement	Measures countries and firms' innovative performance and design policies	OECD
ET	Environmental Technology	Development of environment-related technologies, % all technologies	OECD

Equation (3) and equation (4) present the economic and econometric form of the model 2.

$$EFP = f\ (DI, GDP, TECH, ET) \tag{3}$$

$$lnEFP_t = \alpha_0 + \beta_1\ lnDI_t + \beta_2\ lnGDP_t + \beta_3\ lnTECH_t + \beta_4\ lnET_t + \varepsilon_t \tag{4}$$

3.2. Methodology

3.2.1. Unit root test

The unit root method, suggested by Ref. [44], was used in the study to assess linear regression models with multiple breaks. The dependent variable, y_t, is assumed to be connected to a number of state variables v_{t-1} in this model. Nevertheless, the model says affiliation has been subject to b breaks up at time T:

$$y_t = \gamma'_1 v_{t-1} + \tau_t, \text{where}, t = 1, 2, 3.....T_1$$

$$y_t = \gamma'_2 v_{t-1} + \tau, \text{where}, t = T_1 + 1...T_2$$

$$y_t = \gamma'_b v_{t-1} + \tau_t, \text{where}, t = T_b + 1...T$$

$T_1 \propto T_2 \propto .....\propto T_b \propto T$ and τ_t is a disturbance term. The parameters, breakpoints, and positions are all accurately estimated using the Bai and Perron approach. Breaks are regarded as deterministic regardless of the method used to get them. The maximum number of breaks and the shortest distance between such breaks are requirements for the method. These various breakpoint tests' main goal is to examine the necessity of a fixed coefficient model. If a change point analysis, for example, reveals a break in the description, be replaced by the comparable description projected in two subsamples.

3.2.2. Co-integration test

The study incorporates estimates for long- and short-run elasticities among variables using the ARDL bounds testing method. Furthermore, the element of the ARDL method tolerance of different lags in dissimilar variables makes the technique appealing, multipurpose, and flexible. The ability to host appropriate lags allows for the greatest capture of the data creation process method. Notwithstanding the endogeneity of a few regressors, the ARDL method provides impartial assessments and reliable t-statist [45,46]. In contrast to existing single-equation valuation frameworks, it proposes clear tests for identifying an exceptional co-integration vector concerning assumptions. As a result, the ARDL technique is only useful when there is a rare co-integration vector. The chosen variable order of integration releases the presence of a long run relationship if none of the variables are integrated of order 2. The equation represents the null hypothesis, which states no co-integration between the variables. The cointegration is reported in equation (5).

$$\Delta Y_t = \sigma_0 + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{i=0}^{q} \partial_i \Delta X_{t-i} + \sigma Y_{t-1} + \sigma \Delta X_{t-1} + \varepsilon_t \tag{5}$$

The F-statistics are equivalent to the critical values determined by Ref. [47]. On small samples, the critical values provided by Ref. [48] are more appropriate [47]. displays an asymptotic critical value bounds for the F-statistic table generated as CI. As a result, the F-test has a non-standard distribution and is dependent on Second, the number of regressors determines it; third, whether the ARDL model includes an intercept end/or a trend; and finally, the sample size. It is important to note that critical values generated on a large sample size differ dramatically from critical values generated on a small sample size.

3.2.3. Non-linear ARDL

Researchers suggest that the non-linear ARDL method reports asymmetric results; likewise, this method's assessments are considered complete compared to ARDL. Non–linear ARDL split the data series into two elements, which means a positive shock and a negative shock in the independent variable have different results, and studies the effect of both positive and negative shock on the selected dependent variables [49,50]. In accordance with this technique, this work applies positive and negative changes in the digital index, GDP, technological advancement, and environmental technology, which are fragmented into additional sets of series, mentioned by Ref. [51]. The easiest way to present the model is mentioned in equation (6):

$$Vit = \vartheta_0 + \beta^+ IV_t^+ + \beta^- IV_t^- + e_{it} \text{ and} \Delta IVt = vt \tag{6}$$

V_{jt} and IV_t represents the scalar I (1). V_{jt} denotes the return of i at time t and is distributed into positive and negative shocks. IV_t^+ and IV_t^- represent positive and negative shocks in the independent variable. e_{it} and vt states the random distribution terms.

The positive and negative transformed form of the series are given in equation (7), equation (8), equation (9), equation (10), equation (11), equation (12), equation (13), equation (14).

$$\text{POS}(DI)_t = \sum_{i=1}^{t} lnDI_i^+ = \sum_{i=1}^{t} \text{MAX}(\Delta ln\ \text{DI}_i, 0) \tag{7}$$

$$\text{NEG(DI)}_t = \sum_{i=1}^{t} lnDI_i^- = \sum_{i=1}^{t} \text{MIN}(\Delta ln\ \text{DI}_i, 0) \tag{8}$$

$$\text{POS}(GDP)_t = \sum_{i=1}^{t} lnGDP_i^+ = \sum_{i=1}^{t} \text{MAX}(\Delta ln\ \text{GDP}_i, 0) \tag{9}$$

$$\text{NEG(GDP)}_t = \sum_{i=1}^{t} lnGDP_i^- = \sum_{i=1}^{t} \text{MIN}(\Delta ln\ \text{GDP}_i, 0) \tag{10}$$

$$\text{POS(TECH)}_t = \sum_{i=1}^{t} lnTECH_i^+ = \sum_{i=1}^{t} \text{MAX}(\Delta ln\ \text{TECH}_i, 0) \tag{11}$$

$$\text{NEG(TECH)}_t = \sum_{i=1}^{t} lnTECH_i^- = \sum_{i=1}^{t} \text{MIN}(\Delta ln\ \text{TECH}_i, 0) \tag{12}$$

$$\text{POS(ET)}_t = \sum_{i=1}^{t} lnET_i^+ = \sum_{i=1}^{t} \text{MAX}(\Delta ln\ \text{ET}_i, 0) \tag{13}$$

$$\text{NEG(ET)}_t = \sum_{i=1}^{t} lnET_i^- = \sum_{i=1}^{t} \text{MIN}(\Delta ln\ \text{ET}_i, 0) \tag{14}$$

According to non-linear model, the model 1 and model 2 are breakdown of independent variables such as, digitalization index (*DI*), economic growth (*GDP*), technological advancement (*TECH*), and environmental technology (*ET*) into positive and negative shocks, where $POS(DI)_t$ and $NEG(DI)_t$ are the positive and negative shocks in digitalization index at time *t*. $POS(GDP)_t$ and $NEG(GDP)_t$) are the positive and negative shocks in economic growth at time *t*. Similarly, $POS(TECH)_t$ and $NEG(TECH)_t$ disclose the positive and negative shocks in technological advancement at time *t*, $POS(ET)_t$ and $NEG(ET)_t$ expose the positive and negative shocks in environmental technology at time *t*.

$\text{MAX}(\Delta ln\ \text{DI}_i, 0)$ and $\text{MIN}(\Delta ln\ \text{DI}_i, 0)$ are the maximum and minimum absolute values digitalization index. Moreover, $\text{MAX}(\Delta ln\ \text{GDP}_i, 0)$ and $\text{MIN}(\Delta ln\ \text{GDP}_i, 0)$ are the maximum and minimum absolute values economic growth. Similar illustrations are used for $\text{MAX}(\Delta ln\ \text{TECH}_i, 0)$, $\text{MIN}(\Delta ln\ \text{TECH}_i, 0)$, $\text{MAX}(\Delta ln\ \text{ET}_i, 0)$ and $\text{MIN}(\Delta ln\text{ET}, 0)$ are the maximum and minimum absolute values technological advancement and environmental technology. However, the "0" represents if the values of positive and negative are equal to "0", in this case we have to apply the symmetric ARDL.

Now, the equations are modified by assimilating the negative and positive shocks. The non-linear ARDL equations for two selected models are as follows:

$$\Delta \text{lnEFP}_t = \sigma_0 + \sum_{i=1}^{t} \beta_1 lnEFP_{t-i} + \sum_{i=0}^{t} \beta_2^+ \Delta lnPOS(DI)_{t-i} + \sum_{i=0}^{t} \beta_2^- \Delta lnNEG(DI)_{t-i} + \sigma_0 lnEFP_{t-1} + \sigma_1^+ \Delta lnPOS(DI)_{t-1} + \sigma_1^- \Delta lnNEG(DI)_{t-1} + e_t \tag{15}$$

$$\Delta \text{lnEFP}_t = \sigma_0 + \sum_{i=1}^{t} \beta_1 lnEFP_{t-i} + \sum_{i=0}^{t} \beta_2^+ \Delta lnPOS(GDP)_{t-i} + \sum_{i=0}^{t} \beta_2^- \Delta lnNEG(GDP)_{t-i} + \sigma_0 lnEFP_{t-1} + \sigma_1^+ \Delta lnPOS(GDP)_{t-1} + \sigma_1^- \Delta lnNEG(GDP)_{t-1} + e_t \tag{16}$$

$$\Delta \ln EFP_t = \sigma_0 + \sum_{i=1}^{t} \beta_1 lnEFP_{t-i} + \sum_{i=0}^{t} \beta_2^+ \Delta lnPOS(TECH)_{t-i} + \sum_{i=0}^{t} \beta_2^- \Delta lnNEG(TECH)_{t-i} + \sigma_0 lnEFP_{t-1} + \sigma_1^+ \Delta lnPOS(TECH)_{t-1} + \sigma_1^- \Delta lnNEG(TECH)_{t-1} + e_t \quad (17)$$

$$\Delta \ln EFP_t = \sigma_0 + \sum_{i=1}^{t} \beta_1 lnEFP_{t-i} + \sum_{i=0}^{t} \beta_2^+ \Delta lnPOS(ET)_{t-i} + \sum_{i=0}^{t} \beta_2^- \Delta lnNEG(ET)_{t-i} + \sigma_0 lnEFP_{t-1} + \sigma_1^+ \Delta lnPOS(ET)_{t-1} + \sigma_1^- \Delta lnNEG(ET)_{t-1} + e_t \quad (18)$$

where β_1 and β_2 are the elasticity coefficients for short-run valuations, σ_0 and σ_1 signifies the elasticity coefficients of long-run estimations. POS and NEG signify the positive and negative shocks of each independent variable, and these are employed to examine the asymmetric analysis. Where, equation (15) represents the non-linear impact of DI, equation (16) addresses the non-linear relation of GDP, equation (17) is about the non-linearity of TECH and equation (18) incorporates the non-linear impact of ET on EFP.

4. Results

Table 3 represents the descriptive statistics of the selected dependent and independent variables, and hence the highest standard deviation is obtained for the digital index as 1.197. The variable technological advancement has the highest mean and median at 14.821 and 14.783, respectively.

Later, the methodology applied Quandt-Andrews structural break test to investigate the structural break in data, as mentioned in Table 4. The verdict has established that there is a structural breakpoint. The transferal is due to the participation in Saudi Vison 2030, beginning April 2016. These Vison 2030 policies have led the Kingdom towards economic, ecological, and societal structural reforms, adding special consideration. For additional analysis, the research formulated a dummy variable where the pre-2016 figures is reflected as pre-Vision 2030 and post 2016 data is dealt as post-Vision 2030.

As the data revealed the presence of structural breakdowns, a simple unit root test can help to get more robust results. However, the structural break unit root test is used before employing econometric methodologies, and the results are shown in Table 5. The results show that all variables are stationary at the level and first difference.

The estimations of bound co-integration test are proved to be significant due to the values greater than the upper limit, as given in Table 6. On the other hand, co-integration indicates that selected models have a long-run relationship between independent and dependent variables. Therefore, these observations enable the researcher to employ long- and short-term econometric methodologies to scrutinize the affiliation between the dependent and independent variables.

After scrutinizing the bound co-integration test, there is a need for the linearity and non-linearity test. The intention is to examine the existence of non-linearity in the data series. For this purpose, the study used the BDS test, recommended by Ref. [52], which states that the null hypothesis of "series are linearly dependent". Table 7 approves the implication of series at each dimension, declaring that the selected variables are non-linearly dependent. Nevertheless, it suggested that non-linear ARDL tests execute better results than simple ARDL tests.

4.1. Empirical estimations

Table 8 represents the estimations obtained by applying an empirical approach to pre-Vision 2030 data set. Model 1 estimated a negative relationship between the digitalization index and ecological footprints. A percentage positive shock in the digitalization index decreases ecological footprints by 0.657 %, in the long run. This negative relationship is justified by other researchers such as [19–22]. As non–linear ARDL approach also estimates the negative change, a negative percentage change in the digitalization index depicts an insignificant effect on ecological footprints, according to the results. A few researchers found that a change in digitalization does not matter and has no impact on ecological footprints, similar to Refs. [25,26]. In the short run, the variable digitalization index has an insignificant relationship with ecological footprints. It is observed that there is a need for more digital activities to enhance

Table 3
Descriptive statistics.

	EFP	DI	GDP	TECH	ET
Mean	4.312	13.108	3.513	14.821	5.605
Median	5.312	12.170	3.623	14.783	5.453
Maximum	5.622	13.436	4.107	15.328	6.285
Minimum	4.069	12.721	2.890	14.135	5.088
Std. Dev.	0.317	1.197	0.387	0.434	0.205
Skewness	0.221	0.058	−0.207	0.018	0.810
Kurtosis	1.592	1.921	2.071	1.627	3.465
Jarque-Bera	2.650	1.462	1.329	2.452	3.732
Probability	0.171	0.474	0.531	0.217	0.138

Notes: EFP stands for environmental footprint, DI and GDP are related to digitalization index and economic growth. TECH and ET are indicating the technological advancement and environmental related technologies.

Table 4
Quandt-Andrews structural break test.

Quandt-Andrews structural break test			
	Maximum LR	Expected LR	Average LR
F-Statistics	84.890***	121.652	31.484***

Note: Null hypothesis for Quandt-Andrews test is "no breakpoint". As the results of maximum LR and average LR are significant, however, null hypothesis is rejected, mentioning that there is a structural break in data.

Table 5
Structural break unit root test (Perron unit root test).

Variable	IO		AO	
	Level	Difference	Level	Difference
EFP	0.120	0.000***	0.455	0.000***
DI	0.048**	0.000***	0.034	0.000***
GDP	0.553	0.002***	0.509	0.000***
TECH	0.659	0.001***	0.815	0.000***
ET	0.091*	0.000***	0.075*	0.000***

Notes: IO and AO represent the Innovation outlier and additive outlier. Null hypothesis: the variable has unit root. The values are p-values. ***,**,* shows the level of significance at 1 %, 5 % and 10 %, respectively.

Table 6
Bound co-integration test.

ARDL bounds co-integration Test	F-stat	Result
EFP = f (DI, GDP)	7.531***	Co-integration
EFP = f (DI, GDP, TECH, ET)	7.922***	Co-integration
Lower-bound critical value at 1 %		5.155
Upper-bound critical value at 1 %		6.115
Lower-bound critical value at 5 %		2.438
Upper-bound critical value at 5 %		5.128
Lower-bound critical value at 10 %		2.315
Upper-bound critical value at 10 %		3.915

Table 7
BDS test.

Dimension	EFP	DI	GDP	TECH	ET
2	0.180***	0.112***	0.040***	0.189***	0.129***
3	0.291***	0.162***	0.065***	0.313***	0.266***
4	0.393***	0.189***	0.061***	0.382***	0.318***
5	0.426***	0.189***	0.022	0.413***	0.380***
6	0.417***	0.171***	−0.015	0.452***	0.416***

environmental security.

Furthermore, the findings state that economic growth shows a positive relationship with ecological footprints, that means a 1 % positive change increases the environmental hazards by 0.229 %, in the case of Saudi Arabia. It is important and hence noted by other scholars, such as [7,9,13]. These results contrast [15], which showed a mixed relationship among different countries. In the short run, economic growth depicts a positive relationship with the ecological footprint, which is justified by Ref. [18], the study determined that economic growth instigates emissions to escalate but a gives long-run advantages for income by economic growth to finance environmental policies.

Model 2 focuses on the technological factor and estimates a negative relationship between technological advancement and environmental technologies. A positive change in technological advancement decreases the ecological footprints in the case of Saudi Arabia. Environmental footprints can be decreased by a positive change in environmental-related technologies. In Saudi Arabia, the ecological footprints are increased due to a negative change in technological innovation activities. These results are justified in other economies [16,31,32,35]. The environment is only being supported by technological innovation in the short term, and the increase in technological adoption policies can result in a reduction in carbon emissions. Although the relationship is significant at 10 %, it is considered highly reliable, and there was no short-term impact of environmental technologies. This can be justified by the fact that technological growth stages have different results. Therefore, an impact is seen according to the technology [53]. Environmental technologies are significantly negative, which shows that environmental technology needs consideration to control the environmental

Table 8
Non-linear ARDL estimation (pre-Vision 2030).

Long-run	Model-1	Model-2
EFP $_{t-1}$	0.184	0.145
DI $^{+}$ $_{t-1}$	−0.657**	−0.035***
DI^{-} $_{t-1}$	−0.259	0.248
GDP $^{+}$ $_{t-1}$	0.229*	0.194*
GDP^{-} $_{t-1}$	−0.261	−0.180
TECH $^{+}$ $_{t-1}$		−0.340**
TECH^{-} $_{t-1}$		−0.126**
ET $^{+}$ $_{t-1}$		−0.109***
ET^{-} $_{t-1}$		−0.167
Short-run		
Δ EFP $_{t-1}$	0.234	0.356
Δ DI $^{+}$ $_{t-1}$	−0.417	0.341
Δ DI^{-} $_{t-1}$	0.0.21	0.091
Δ GDP $^{+}$ $_{t-1}$	0.245*	0.211*
Δ GDP^{-} $_{t-1}$	0.186	0.146
Δ TECH $^{+}$ $_{t-1}$		−1.258*
Δ TECH^{-} $_{t-1}$		−0.064
Δ ET $^{+}$ $_{t-1}$		−0.156
Δ ET^{-} $_{t-1}$		0.145
Constant	−10.872***	−8.915**

Notes: ***,**,* represents the level of significance at 1 %, 5 % and 10 % respectively.

footprint.

Table 9 demonstrates post-Vision 2030 estimation; at this time of era Saudi Arabia has taken favorable measures towards environmental solutions and especially commenced projects to fulfill better needs of individuals. This digitalization index has a negative and significant relationship with ecological footprints and contributes more as the coefficient is 1.405 at 5 % significance level. The results found that more a 1 % increase in digitalization index in the short run decreases ecological footprints by 0.651 % at 5 % significance level [54]. justified these long and short run relationships with ecological footprints and declared the importance of digitalization towards ecological security. Considering the variable economic growth, it has a positive relationship but with less magnitude of impact as compared to pre-vision 2030 outcomes because of more sustainable growth goals for urbanization and energy consumption.

The findings estimate that technological advancement has a negative relationship and declared that a positive percentage change in technological advancement decreases ecological hazard by 0.451 %, at 1 % significance level. Therefore, Saudi Arabia's relationship is crucial, and policies are achieving fruitful results by opting for sustainable goals for Vision 2030. Environmental-related technologies have a negative relationship, similar to pre-Vision 2030, but the effect is more as environmental support policies decrease more carbon footprints from the environment by less energy usage. In the short run, there is a positive relationship between economic growth with ecological footprints and a negative relationship between technological advancement, environmental-related technologies, and

Table 9
Non-linear ARDL (post-Vison 2030) estimations.

Long-run	Model-1	Model-2
EFP $_{t-1}$	0.154	0.126
DI $^{+}$ $_{t-1}$	−1.405**	−0.300***
DI^{-} $_{t-1}$	−0.041	−0.061
GDP $^{+}$ $_{t-1}$	0.218*	0.181*
GDP^{-} $_{t-1}$	−0.232	−0.170
TECH $^{+}$ $_{t-1}$		−0.451**
TECH^{-} $_{t-1}$		−0.226*
ET $^{+}$ $_{t-1}$		−0.519*
ET^{-} $_{t-1}$		−0.237
Short-run		
Δ EFP $_{t-1}$	0.021	0.325
Δ DI $^{+}$ $_{t-1}$	−0.651***	0.054**
Δ DI^{-} $_{t-1}$	0.610	0.010
Δ GDP $^{+}$ $_{t-1}$	0.174*	0.159*
Δ GDP^{-} $_{t-1}$	0.034	0.032
Δ TECH $^{+}$ $_{t-1}$		−1.358**
Δ TECH^{-} $_{t-1}$		−0.078*
Δ ET $^{+}$ $_{t-1}$		−0.142*
Δ ET^{-} $_{t-1}$		0.136
Constant	−11.872***	−9.615***

Notes: ***,**,* represents the level of significance at 1 %, 5 % and 10 % respectively.

ecological footprints.

Table 10 represents estimations about post Covid19 situations and results that the digitalization index has a negative relationship with ecological footprints in both the long and short run. But digital activities used after the pandemic provides more significant results at 5 % in case of the short run. This is justified as [55] stated that Saudi Arabia launched 19 apps in favor of e-learning, risk communication, and health care services. This reduces the ease of many human activities raising carbon emissions such as transportation and paper waste from regular schools [56]. states that remote learning reduces ecological footprints in terms of mobility. The magnitude has increased; therefore, in post-pandemic estimations 1 % percentage positive change in the digitalization index decreases the ecological footprints by 2.405 %. It has been seen that negative change in GDP reduces ecological footprints by 0.032 %, which is significant at 10 %. Technological factor depicts a negative relationship and contributes to reducing ecological footprints for Saud Arabia [57]. concluded that environmental-related technologies mitigate carbon emissions [58]. justified that ecological-friendly patents, as well as environmental duties, decline CO_2 in OCED countries.

4.2. Discussion

The study describes important findings for policymakers and discloses that the digitalization index has a negative impact on ecological footprints in the long run. This means an increase in digital economic activities decreases the ecological footprints in Saudi Arabia. The post-vision 2030 results declare similar results, but the magnitude of impact is higher. Digital activities incorporate business communication systems; emails reduce paper waste, e-commerce reduces transportation energy consumption, and e-banking minimizes human activities [59]. Therefore, the internet reduces energy usage through transportation, network, industrial production, smart cities etc. [27,60]. Smart solutions decrease energy consumption and hence are favorable for the environment. As digitalization enhances the service industry, it takes a boost. Therefore, service sectors are thought to be less carbon-intensive than manufacturing and production industries. An important finding is that the digitalization index significantly impacted the environment in the short run. Hence, it is believed that digitalization started its favorable environmental results for achieving Vision2030 goals.

Economic growth has a positive relationship with ecological footprints, obtained in pre and post-Vision 2030 results. Before Vision 2030, Saudi Arabia's major economic growth depends on oil; therefore, the increase in oil consumption is strongly responsible for ecological footprints. In the case of post-Vision 2030, Saudi Arabia is heading towards urbanization, and urbanization contributes to more ecological footprints, as mentioned by researchers [61,62]. The country is shifting to tourism activities and hence willing to shift oil-generated revenue to other sources. Tourism needs attracted places; hence more nonenergy development projects enhance energy usage such as electricity consumption, transportation consumption etc. Therefore, it contributes to the ecological footprint of the county. Saudi Arabia announced nine mega-projects for construction between 2016 and 2020, named NEOM, the Red Sea Project, and Qiddiya, and plans to capitalize another $1.5 trillion in the tourism industry over the next decade. Thus, in both time frames, economic development increases ecological hazards in the country.

Technological advancement and environmental-related technologies obtained a negative relationship with the ecological footprint. Thus, more environmental support technologies decrease non-renewable energy consumption, and environmental-related technologies provide less energy consumption, hence less ecological footprints. Compared to pre and post Vision 2030 estimations, environmental technologies significantly impact the Post Vision 2030 era. This can be justified by the policies adopted to lower fossil consumption and improve energy efficiency in the country. Many projects have started, such as Saudi Arabia has cited ACWA Power in the middle of its Vision 2030 goal to replace oil power production and to produce 50 percent of its electricity from renewable sources. Saudi Arabia has initiated and constructed several major renewable energy projects, captivating the advantage of its natural resources in solar and wind. All these can be seen by the results and the positive impact of technological improvements and environmental-related technologies growing towards ecological health as time passes.

In post-COVID-19 estimations, the digitalization index has an inverse relationship with ecological footprints. In COVID-19, human activities got limited, and the digital sector has been more focused on e-commerce, e-learning/education system, and online learning. This is observed that oil prices dropped due to less consumption by vehicles, and transportation has favored environmental security. Therefore, economic growth has a positive relationship with ecological footprints and a significant negative change in economic growth depicts the falloff economic GDP post-pandemic timeframe. Statics declared a drop in GDP from 803.6 billion USD (2019) to 703.4 billion USD (2020). Saudi Arabia being an oil-dependent economy, got affected in terms of GDP, but this significance level cannot completely justify the impact on ecological footprints. The environmental improvements after COVID-19 were clearly due to a lack of human activities. In view of environmental-related technologies and technological advancement, post-pandemic results alike with post Vision2030 era. The project initiated was not halted, and Saudi Arabia continued their sustainable goal achievement.

5. Conclusion

This study explores the role of the digitalization index, economic growth, technological advancement, and environmental-related technologies toward Ecological footprints in Saudi Arabia economy over the past two decades (1998–2022). It applies the non-linear ARDL approach while estimating the non-linearity between the stated variables in short-run and long-run intervals. The outcomes through non-linear ARDL estimation reflect that estimated values of positive change of the digitalization index are significantly negative, and economic growth has a significant positive relationship with ecological footprints. Moreover, another significant contribution associated with this research confirms the existence of technological advancement and environmental-related technologies, confirming the reduction of ecological footprints as it increases. The digitalization index confirms the significant role of countering the environmental challenges, especially in post-Vision 2030 and post-COVID-19 estimations. Similarly, environmental-

Table 10
Non-linear ARDL Post COVID-19 estimations.

Long-run	Model-1	Model-2
EFP_{t-1}	0.187	0.152
DI^{+}_{t-1}	−2.405*	−0.256***
DI^{-}_{t-1}	−0.051	−0.042
GDP^{+}_{t-1}	0.119*	0.191*
GDP^{-}_{t-1}	0.032***	−0.170
$TECH^{+}_{t-1}$		−0.521*
$TECH^{-}_{t-1}$		−0.236*
ET^{+}_{t-1}		−0.299*
ET^{-}_{t-1}		−0.237
Short-run		
ΔEFP_{t-1}	0.034	0.215
ΔDI^{+}_{t-1}	−0.891**	0.023**
ΔDI^{-}_{t-1}	0.610	0.020
ΔGDP^{+}_{t-1}	0.174*	0.139*
ΔGDP^{-}_{t-1}	0.034***	0.032
$\Delta TECH^{+}_{t-1}$		−1.568**
$\Delta TECH^{-}_{t-1}$		−0.026*
ΔET^{+}_{t-1}		−0.152*
ΔET^{-}_{t-1}		0.176
Constant	−12.882***	−9.815***

Notes: ***,**,* represents the level of significance at 1 %, 5 % and 10 % respectively.

related technologies and technological innovation are seen as helpful in reducing environmental threats that reaffirm the country's efforts. These outcomes have been observed in the post-Vision 2030 time frame results, which depict the sustainable goals adopted by the policymakers. In Post COVID-19 estimations, economic growth has seen significant negative change due to the GDP reduction in 2020.

There are some important policy implications for the country, such as policymakers should concentrate more on renewable energy technologies improvements. The recommendations of COP26 and COP27 should be accelerated to control the environmental challenges. The contribution of environmental-related technologies is needed as the shift from oil-generating economic growth requires more focus on natural and renewable resources. Another recommendation is that the country eases green innovation and technologies implementation rules and regulations with fewer taxes and fees. The country should balance digitalization activities as it can generate more technological waste and electricity consumption in later stages. This research can further be improved by evaluating the industry level. Each industry has different resources and technology; therefore, the usage level can vary its impact on ecological footprints. Moreover, comparing GCC countries can further enhance the literature and elaborate on the ecological footprint situation.

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