



Revisiting the environmental Kuznets curve hypothesis with globalization for OECD countries: the role of convergence clubs

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Received: 5 August 2022 / Accepted: 23 January 2023 / Published online: 3 February 2023
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Abstract

This paper aims to investigate the role of globalization in ecological footprint for Organization for Economic Cooperation and Development (OECD) countries during the 1981–2015 period with the environmental Kuznets curve (EKC) framework. To do so, unlike the existing literature, we follow a different path. Firstly, we test the environmental convergence (EC) hypothesis using the Phillips and Sul, *Econometrica* 75(6): 1771–1855, (2007) methodology. Then, we examine the impact of globalization and energy consumption on the ecological footprint (EF), and test the existence of the EKC hypothesis using the dynamic ordinary least squares mean group (DOLSMG) estimator. The convergence test results indicate that OECD countries do not converge to the same steady-state levels with regard to EF levels. However, we identify two convergence clubs that converging to a different steady-state equilibrium. The results of DOLSMG reveal that the EKC hypothesis is valid for both convergence groups. Furthermore, the impact of energy consumption and globalization on EF is higher for club 2, which includes developing countries.

Keywords Ecological footprint · Club convergence · Environmental Kuznets curve · Globalization

Introduction

The anthropogenic pressure on the environment is a catastrophic threat facing humanity. Although global efforts to prevent environmental degradation and use renewable energy in this direction are gradually increasing, fossil fuel use continues to be the primary energy source worldwide. The use of fossil fuels increases environmental degradation by causing an increase in greenhouse gas (GHG) emissions. Moreover, the disparities in the economic development levels and growth prospects of the countries cause the damage to the environment to differ between countries. The geographical distribution of GHG emissions does not affect the total amount of GHG emissions in the atmosphere, but this distribution is an essential topic of multinational discussions on climate change (Aldy 2006). Since carbon dioxide (CO₂) emissions are an important component of GHG emissions,

discussions on how to reduce these emissions are ongoing. The convergence of these pollution indicators is regarded as a key goal in global efforts to stop environmental degradation, such as the Kyoto Protocol and the Paris Agreement. However, there are three issues that need to be addressed regarding these negotiations. Firstly, targeting convergence in environmental indicators is critical in terms of equality and fairness (Aldy 2006; Barassi et al. 2011; Payne et al. 2014). Secondly, the main focus in these negotiations is to reduce CO₂ emissions, even though there are other environmental problems such as water pollution, soil and land pollution, and deforestation. Thirdly, as a result of these negotiations, success has yet to be achieved in preventing environmental degradation. On the other hand, to limit global warming to 1.5 °C, no more than 28 gigatons of CO₂ equivalent should be released into the atmosphere annually until 2030 (UNEP 2021). Given the recent emissions trend,¹ it is clear that we have a finite amount of time to reduce CO₂ emissions.

Multinational negotiations on environmental degradation have also begun attracting researchers' attention. In this direction, the question of whether countries converge from

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¹ For instance, total CO₂ emissions were 33 gigatons in 2021 (IEA 2021).

the standpoint of environmental degradation has become popular among researchers, and this subject has been analyzed in the EC framework (Apaydin et al. 2021). The theoretical basis of EC is derived from the EKC hypothesis introduced by Brock and Taylor (2004). As shown in the EKC literature, with an increase in efforts to stop environmental degradation and the use of cleaner technologies, environmental degradation rises to a particular income level and then decreases. According to this model, as countries get richer, it is expected that the growth rate of emission rates will decrease and emission rates will converge (Acar and Lindmark 2017). Although there are different methods for measuring convergence (beta, sigma, and stochastic), the club convergence method is mainly used in recent studies (see Panopoulou and Pantelidis 2009; Herrerias 2012; Ulucak and Apergis 2018; Haider and Akram 2019; Solarin et al. 2019; Erdogan and Okumus 2021; Payne and Apergis 2021). The club convergence methodology introduced by Phillips and Sul (2007, 2009) enables us to test overall convergence and determine possible convergence clubs.

In the literature, several indicators have been employed different proxies for environmental degradation. The two most commonly used indicators in the literature are EF and CO₂ emissions. While early studies primarily used CO₂ emissions, recent studies have mainly focused on the EF proposed by Rees (1992) and developed by Wackernagel (1994) and Wackernagel and Rees (1996). EF is a measure of the total area of biologically productive land and water, measured in global hectares, required to produce the natural resources humans consume and absorb environmental degradation from human activities (Global Footprint Network 2021). Therefore, EF comprises not only CO₂ emissions but also other environmental degradation in the quality of water, soil, forest land, grazing land, built-up land, the footprints of fishing ground, and cropland (Destek and Sinha 2020; Sharma et al. 2021; Ansari et al. 2022; Yasin et al. 2022). Since EF is a more comprehensive indicator than CO₂ emissions as a proxy for environmental degradation, we prefer to use EF.

One of the factors that is widely considered an essential factor in environmental degradation is globalization. Globalization can generally be defined as the economic, political, and social integration of countries. The impact of globalization on the environment takes place in different directions and with different factors. First, increasing international trade with globalization leads to a rise in CO₂ emissions due to transportation. Second, the increase in international trade and investments stimulates the economic growth, especially in developing countries. But these increasing activities also enhance environmental degradation due to the increasing consumption of electricity, which is still mostly produced from fossil fuels. Third, with globalization, deforestation has also accelerated, which indirectly

but significantly affects environmental degradation (Jean-Yves and Loïc, 2013). Finally, it has increased environmental awareness worldwide, and in this direction, international negotiations for the prevention of environmental degradation have gained momentum. Many studies have investigated globalization's impacts on the environment in recent years. Some of these studies employed trade openness as an indicator of globalization (Halicioglu 2009; Jayanthakumaran et al. 2012; Shahbaz et al. 2012, 2015; Farhani et al. 2014; Lau et al. 2014; Haq et al. 2016; Acaravci and Akalin 2017; Chen et al. 2019a; Pata 2019; Dauda et al. 2021; Pata and Caglar 2021; Wang and Zhang 2021; Wang and Wang 2021)). However, trade openness covers only the international trade dimension of globalization. Since globalization has other dimensions, such as capital flows, information flows, and political and social aspects, globalization indices are used in recent studies (Shahbaz et al. 2017; Haseeb et al. 2018; Ahmed et al. 2019; Khan and Ullah 2019; Phong 2019; Zaidi et al. 2019; Ansari et al. 2020; Godil et al. 2020; Saud et al. 2020; Suki et al. 2020; Hussain et al. 2021; Jun et al. 2021). In order to account for various aspects of globalization, we use the KOF globalization index, introduced by Dreher (2006) and developed by Gygli et al. (2019). The KOF globalization index covers the economic, social, and cultural dimensions of globalization.

Within this context, we examine the impact of globalization on EF and the existence of the EKC hypothesis for OECD countries over the period 1981–2015 using the dynamic ordinary least squares mean group (DOLS MG) estimator. We chose to focus on the OECD countries for several reasons. First, the OECD mostly consists of developed countries that account for approximately 60% of the world's GDP (measured in constant 2015 US dollars) in 2021 (WDI 2022). Second, OECD countries are historically considered the highest polluters. These countries emit about 33% of global CO₂ emissions, and the OECD's per capita CO₂ emissions (7.5 tons) are much higher compared to the world's average (4.1 tons) (IEA 2022). However, OECD country-specific rates vary significantly for reasons such as composition and rate of economic growth, socio-demographic developments, energy supply and consumption patterns, energy prices, and differences in environmental policies (OECD 2022). Third, the share of renewable energy in final energy consumption is also higher in OECD countries (13.7%) than the world average (11.5%) (IEA 2022). Finally, as Yilanci et al. (2019) stated, data reliability is higher due to the more developed institutions in these countries. However, unlike the existing literature, we follow a different path by considering the EC hypothesis. In the current literature, most studies analyze the EKC hypothesis for a single country or a group of countries. But OECD countries are not homogeneous in terms of EF per capita. For instance, the EF per capita in the USA is three times of that in Mexico. So, testing the

EKC hypothesis for OECD countries in the same basket may cause misleading results. Thus, we first test the EC hypothesis using the non-linear dynamic factor model introduced by Phillips and Sul (2007). After identifying EF convergence clubs, we test the EKC hypothesis and the impact of globalization and energy consumption on EF for each convergence club (that is, a more homogeneous group of countries in terms of EF per capita) and full panel. In this context, this study contributes to the literature by being the first study to test the EKC hypothesis for OECD countries within the framework of the EC hypothesis. The rest of the study is organized as follows: “Literature review” summarizes the related empirical literature. “Empirical analysis” illustrates the empirical analysis and results. Finally, “Conclusion and policy implication” concludes the paper.

Literature review

As mentioned above, we follow a two-step procedure in this paper. First, we test the convergence in ecological footprints across OECD countries. Next, we test the EKC hypothesis with the role of globalization. Therefore, we divide the literature part into two sections. The first section gives the literature on the environmental convergence hypothesis. The second section provides the related literature on the EKC hypothesis with the role of globalization, and studies analyzing the impact of globalization on environmental degradation. We also classify the studies of the effects of globalization on environmental degradation into two categories according to the proxy for environmental degradation, which are ecological footprint and CO₂ emissions.

Environmental convergence hypothesis

The environmental convergence hypothesis has been examined using various environmental degradation indicators. It is observed that the literature on the environmental convergence hypothesis follows two paths regarding the environmental degradation indicator: (i) studies using carbon dioxide emissions and (ii) studies using the ecological footprint. The findings of these studies differ. Some studies show the existence of convergence, while others reveal no convergence across global, states, country groups, or sector levels.

The first group of studies focuses on CO₂ emissions as an environmental indicator. For instance, Nguyen Van (2005) tests the convergence in CO₂ emissions among 100 countries for the 1966–1996 period using the non-parametric method and finds no convergence. Aldy (2006) investigates the convergence in CO₂ emissions across 88 countries from 1960 to 2000, and the results support the absence of convergence. Ezcurra (2007) tests the distribution of CO₂ emissions among 87 countries over 1960–1999 following a

non-parametric method. The findings show that cross-country disparities decrease over time. Westerlund and Basher (2008) examine the convergence in CO₂ emissions across 16 developed and 12 developing countries over 1870–2002, employing unit root test methods. They find a stochastic convergence for the full panel. Unlike these studies, Pano-poulou and Pantelidis (2009) follow the club convergence method to test the convergence in CO₂ emissions across 128 countries for the 1960–2003 period. The results reveal that there are two convergence clubs. Similarly, Herrerias (2012) investigates whether CO₂ emissions among 162 countries convergences over 1980–2009 using the Phillips and Sul (2007, 2009) method and pairwise test approach. The results of the pairwise test show that there is no convergence across countries. However, according to the findings of club convergence analysis, there are multiple convergence clubs. Li et al. (2020) test the convergence of global CO₂ emissions across 129 countries for the 1995–2015 period using sigma, beta, stochastic, and club convergence methods. The findings reveal that global CO₂ emissions are convergent, and the speed of convergence of consumption is slower than that of production. Burnett (2016) tests the convergence in CO₂ emissions among the 48 US states for the period of 1960–2010 using club convergence and conditional beta convergence methods. The findings reveal that there is one convergence club for 26 states. Apergis et al. (2017) examine the convergence intensity of CO₂ emissions across 50 US states for 1997–2013, the period using cross-sectional tests methods. The results support the existence of sigma and beta convergence, while there is no stochastic convergence across states. Tiwari et al. (2021) conclude that there are four clubs across US states over 1976–2014. Solarin (2014) tests the convergence in CO₂ emissions across 39 African countries for the period of 1960–2010 using the univariate unit root test method. The findings confirm the existence of stochastic convergence for 31 countries. Robalino-Lopez et al. (2016) test the convergence in CO₂ emissions for 10 South American countries for the 1980–2010 period. According to the results, there are two convergence clubs for CO₂ emissions and energy intensity. Tiwari and Mishra (2017) reveal absolute beta convergence and sigma convergence for 18 Asian countries over 1970–2010. Karakaya et al. (2019) conclude that there is a stochastic convergence in CO₂ emissions across 16 industrialized OECD countries for the 1990–2013 period.

Some studies in the literature focus on convergence at sector levels. For example, Moutinho et al. (2014) examine the convergence in CO₂ emissions intensity across 16 Portuguese energy and industry sectors over 1996–2009 using univariate and unit root test methods. The findings show the existence of stochastic convergence among sectors. Brännlund et al. (2015) conclude a conditional beta convergence in CO₂ emissions intensity for 14 Swedish

manufacturing sectors over 1990–2008. Similarly, Apergis and Payne (2017) test the convergence in per capita CO₂ emissions among 50 US states by sector level and fossil fuel source using panel unit root test methods. The findings support the existence of stochastic convergence.

The second group of studies focuses on convergence in EF as an environmental degradation indicator. For instance, Ulucak and Apergis (2018) investigate the club convergence in EF for EU countries for the period of 1961–2013, employing the Phillips and Sul (2007) method. The results confirm that there are convergence clubs. Similarly, Bilgili and Ulucak (2018) study the convergence in EF in G20 countries from 1961 to 2014. According to the findings, the club clustering algorithms support the presence of convergence clubs. Using the residual augmented least squares Lagrange multiplier (RALS-LM) and Lagrange multiplier (LM) unit root tests methods, Solarin (2019) examines whether the carbon footprint, CO₂ emissions, and EF converge among OECD countries for the period of 1961–2013. The findings show a conditional convergence in these indicators across countries. Ulucak et al. (2020a) investigate the convergence in EF and its sub-components across 23 African countries for the 1961–2014 period. The findings indicate convergences for carbon, cropland, grazing land, and fishing ground footprints. Erdogan and Okumus (2021) analyze the convergence process for EF over 1961–2016 using the club convergence method. The results show two convergence clubs for middle- and low-income countries and four for high-income countries. Apaydin et al. (2021) use the club convergence method to examine EF convergence in 130 countries from 1980 to 2016 and conclude multiple convergence clubs across these countries.

Impact of globalization on environmental degradation

Over the last three decades, the role of globalization in environmental degradation has been investigated by researchers applying various econometric techniques and samples. Thus, the results of the studies differ significantly. Some studies confirm that globalization impacts environmental degradation positively, while other studies reveal that globalization impacts environmental degradation negatively. We can classify the related literature into two categories: (i) the first group of studies uses CO₂ emissions and (ii) the second group of studies uses EF as a proxy for environmental degradation.

Impact of globalization on CO₂

The first group of studies in the literature uses trade openness as a proxy for globalization. For instance, Lau et al. (2014) find a positive relationship between foreign direct

investments (FDI), trade openness, and CO₂ emissions for Malaysia over 1970–2008 using autoregressive distributed lag (ARDL)-bound testing method. The results verify the existence of the EKC hypothesis. Shahbaz et al. (2015) find a positive relationship between CO₂ and trade openness for Portugal over 1971–2018, and the findings confirm the EKC hypothesis. Haq et al. (2016) reveal that an increase in trade openness decreases carbon emissions for Morocco over 1971–2011, and the results show the existence of the EKC hypothesis. Using the bootstrap ARDL approach, Pata (2019) shows that a rise in trade openness stimulates CO₂ emissions in Turkey over 1969–2017, and the results support the validity of the EKC hypothesis. Dauda et al. (2021) show that a rise in trade openness decreases the CO₂ emissions in African countries over 1990–2016, performing a fixed-effect model and generalized method of moments panel estimation models. Pata and Caglar (2021) find that trade openness increases CO₂ emissions in China over 1980–2016. The results reveal that the EKC hypothesis is invalid for both EF and CO₂ emissions. Kongkuah et al. (2022) test the relationship between economic growth, urbanization, energy consumption, international trade, and CO₂ emissions in China for the period of 1971–2014 using the fully modified ordinary least squares (FMOLS) approach regarding the EKC hypothesis. The results reveal that international trade increases CO₂ emissions, and that the EKC hypothesis is not valid for China.

The second group of studies uses the KOF globalization developed by Dreher (2006), which is more comprehensive than trade openness, as a proxy for globalization. Some studies conclude that globalization decreases CO₂ emissions. For instance, Shahbaz et al. (2017) investigated globalization' and sub-indices impact on CO₂ over 1970–2012 in China. The results show that globalization is negatively related to CO₂ emissions for China, and the EKC hypothesis is valid. Zaidi et al. (2019) study the relationship between globalization, financial development, and CO₂ emissions in Asia–Pacific Economic Cooperation (APEC) countries and analyze the EKC hypothesis. The findings reveal that the negative relationship between globalization and carbon emissions, and the EKC hypothesis is valid for APEC countries. Using Westerlund cointegration, Balsalobre-Lorente et al. (2020) test the link between globalization and CO₂ emissions in OECD countries over 1994–2014 using the FMOLS approach. The findings show that globalization reduces CO₂ emissions. Islam et al. (2021) investigate the impact of globalization on CO₂ emissions in Bangladesh over 1972–2016 using the dynamic ARDL methodology. The results indicate that globalization affects environmental quality positively. Tahir et al. (2021) investigate the link between globalization and CO₂ emissions in South Asian countries over 1990–2014 using FMOLS and dynamic ordinary least squares (DOLS) methods. The results show that

globalization decreases environmental degradation. Awan and Azam (2022) test the link between social globalization and CO₂ emissions regarding the EKC hypothesis for the G-20 countries. The results of the LM bootstrap method reveal that social globalization reduces environmental degradation. On the other hand, many studies in the literature reveal that globalization causes an increase in CO₂ emissions. For instance, Chen et al. (2019b) test the link between globalization and CO₂ emissions in Central and Eastern European countries for the period of 1980–2016 using dynamic seemingly unrelated regression (DSUR) and Dumitrescu-Hurlin causality methods. The results confirm that the EKC hypothesis is valid and there is a two-way causal relationship between variables. Using ARDL methodology, Khan and Ullah (2019) analyze the link between globalization sub-indices and CO₂ emissions in Pakistan over 1975–2014. They conclude that an increase in social, political, and economic globalization increases CO₂ emissions and the EKC hypothesis is valid in Pakistan. Phong (2019) tests the link between globalization and CO₂ emissions in the Association of Southeast Asian Nations (ASEAN)-5 countries for the period of 1971–2014 regarding the EKC hypothesis. The findings of regression models reveal that globalization increases CO₂ emissions, and these findings confirm the existence of the EKC hypothesis in ASEAN-5 countries. Rafindadi and Usman (2019) investigate the relationship between globalization and CO₂ emissions in South Africa over 1971–2014 using the Maki cointegration test. The results confirm that the EKC hypothesis is valid for South Africa and globalization increases environmental degradation. Le and Ozturk (2020) investigate the relationship between globalization and CO₂ emissions in 47 emerging markets and developing economies over 1990–2014 using common correlated effects mean group (CCEMG), augmented mean group (AMG), and dynamic common correlated effects (DCCE) estimators with regard to the EKC hypothesis. According to the findings, globalization increases CO₂ emissions, and the EKC hypothesis is confirmed. Usman et al. (2020) investigate the globalization CO₂ emissions nexus regarding the EKC hypothesis in South Africa over 1971–2014 using the FMOLS method. The findings confirm the validity of the EKC hypothesis and globalization increases environmental degradation. Adebayo et al. (2021) test the link between globalization and CO₂ emissions in South Korea for the period of 1980–2018 using panel ARDL methodology. The findings show that globalization increases environmental degradation. Jun et al. (2021) analyze the impact of globalization on CO₂ emissions for South Asian economies over 1985–2018. The results confirm the EKC hypothesis and indicate that globalization positively affects CO₂ emissions. Nathaniel et al. (2021) test the link between globalization and CO₂ emissions in Latin American and Caribbean countries over 1990–2017

using AMG and CCEMG methods. The results show that globalization decreases the negative impact of urbanization on environmental quality. Also, a feedback causality exists between globalization, economic growth, urbanization, and CO₂ emissions. Akadiri et al. (2022) test the link between globalization and CO₂ emissions in Nigeria over 1971–2018 using quantile–quantile approach. The findings show that globalization positively impacts environmental degradation in all quantiles. Oladipupo et al. (2022) investigate the relationship between globalization and CO₂ emissions in South Africa over 1970–2018 using the quantile regression methodology. The results show that globalization worsens environmental degradation in the majority of quantiles. Unlike these studies, Haseeb et al. (2018) find that the link between CO₂ emissions and globalization is not statistically significant in BRICS economies; however, the findings confirm the existence of the EKC hypothesis.

Impact of globalization on ecological footprint

Over the past years, EF has been widely used as an indicator for environmental deterioration, as it is a more comprehensive indicator than carbon emissions. Similar to the studies analyzing the link between carbon emissions and globalization, the first group uses trade openness as an indicator of globalization. Al-mulali et al. (2015) find that trade openness increases EF for 93 countries. Furthermore, the findings reveal that the EKC hypothesis is valid in high- and upper-middle-income countries, whereas it is not valid for middle- and low-income countries. Ozturk et al. (2016) study the link between energy consumption, urbanization, tourism, trade openness, and EF for 144 countries over 1988–2008. They find a negative relationship between EF and other variables, and the EKC hypothesis is only valid for the upper-middle-income and high-income countries. Destek and Sinha (2020) detect a negative relationship between EF and trade openness across 24 OECD countries over 1980–2014. The findings do not support the EKC hypothesis. Yasin et al. (2020) investigate the impact of financial development, trade openness, urbanization, energy consumption, and political institutions on EF in 110 countries over 1996–2016 using panel estimated generalized least squares (EGLS) and multi-step generalized moments of methods (GMM) methods regarding the EKC hypothesis. The results show that trade openness, urbanization, and political institutions decrease environmental degradation, while financial development increases it. Kirikkaleli et al. (2021) test the link between trade openness and EF in Turkey using FMOLS and DOLS approaches. According to the results, trade openness reduces EF in the short run. Yasin et al. (2022) test the impact of financial development, energy consumption, ethnicity diversity, and urbanization on ecological footprint and CO₂ emissions in 51 less-developed countries for the period of 1996–2016.

The findings of the GMM analysis reveal that financial development and energy consumption increase environmental degradation.

Other groups of studies use the KOF index as an indicator of globalization. Some studies find that globalization reduces the ecological footprint. For instance, Ibrahim and Hanafy (2020) investigate the link between globalization and EF in Egypt for the period of 1971–2014 using FMOLS and DOLS methods. The results reveal that globalization reduces the ecological footprint. Pata and Yilanci (2020) test the relationship between globalization and EF in G-7 countries using a Fourier test and threshold cointegration test. The results show that globalization decreases EF in Canada and Italy in the long term. Saud et al. (2020) analyze the link between financial development, globalization, and EF for selected one-belt-one-road initiative countries. The results indicate a positive relationship between EF and financial development and a negative one between EF and globalization. Ulucak et al. (2020b) test the relationship between financial globalization and EF in 15 emerging countries over 1974–2016 using mean group (MG), pooled mean group (PMG), and DOLS methods. The results show that financial globalization improves environmental quality. Salari et al. (2021) investigate the globalization-EF nexus in 21 emerging countries over 2002–2016 using the panel quantile regression method. The results show that globalization has a negative impact on EF in all quantiles. Ansari et al. (2022) investigate the relationship between globalization and EF in G-20 countries over 1991–2016 regarding the EKC hypothesis using FMOLS and DOLS approaches. The results show that globalization improves environmental quality and the EKC hypothesis is valid. Using Fourier bootstrap ARDL methodology, Alper et al. (2022) conclude that globalization reduces EF in the top ten countries with the highest carbon emissions from 1970 to 2017. Alvarado et al. (2022) test the link between globalization and EF in 95 countries for the period of 1990–2018 using AMG, CCEMG, and dynamic correlated effects (DCCE) approaches. According to the findings, globalization improves environmental quality.

In contrast, some studies show that globalization increases EF. For example, using multivariate regression models, Figge et al. (2017) conclude that globalization increases EF in 171 countries. Sabir and Gorus (2019) investigate the relationship between globalization and EF in South Asian countries regarding the EKC hypothesis for the period of 1975–2017 using the ARDL method. The results show that globalization increases environmental degradation. Using the Bayer and Hanck cointegration test and the ARDL bound methods, Ahmed et al. (2019) test the impact of globalization on the EF for Malaysia over 1971–2014. The findings indicate that globalization significantly increases the ecological carbon footprint. Ansari et al. (2020) conclude that globalization impacts the EF positively in Gulf Cooperation

Council (GCC) countries over 1991–2017, applying the DOLS and FMOLS models. Their findings do not support the validity of the EKC hypothesis. Langnel and Amegavi (2020) test the link between globalization and EF in Ghana over 1971–2016 using the ARDL model. The findings indicate that globalization decreases environmental quality. Godil et al. (2020) find a positive relationship between globalization and EF, and the authors identify the existence of the EKC hypothesis for Turkey over 1986–2018. Ahmed et al. (2021) test the link between economic globalization and EF in Japan over 1971–2016 using Narayan-Popp and Clemente-Montanes-Reyes (CMR) unit root tests and symmetric and asymmetric ARDL models. According to the symmetric results, economic globalization increases EF in the long term. On the other hand, asymmetric results show that positive and negative changes in economic globalization decrease EF. Alola et al. (2021) use panel ARDL methodology to examine the relationship between globalization and EF in the top ten destination countries from 1995 to 2016. The results reveal that an increase in globalization increases EF. Hussain et al. (2021) identify a significant and non-linear relationship between globalization, natural resources, and EF and support the validity of the EKC hypothesis for Thailand over 1970–2018. Rehman et al. (2021) test the link between EF and globalization in Pakistan over 1974–2017 using the ARDL method. The findings indicate that globalization increases EF. Guan et al. (2022) test the relationship between globalization and EF in G-10 countries for the period of 1995–2019 using the cross-sectional ARDL method. The findings indicate that globalization increases EF. Mishra and Dash (2022) test the economic globalization and EF nexus in 5 South Asian countries over 1971–2019 using the panel ARDL model. The results show that globalization increases EF. Sadiq and Wen (2022) investigate the relationship between globalization and EF in the 10 largest ecological footprint countries over 1990–2017 using the feasible general least squares (FGLS) approach. The results show that globalization increases environmental degradation. Wang et al. (2022) test the impact of globalization on EF and CO₂ emissions in South Asian countries over 1990–2018 using FMOLS and DOLS methods. The results reveal that globalization increases environmental degradation. Wenlong et al. (2022) test the link between economic globalization and the EF in USA over 1995–2018 using the quantile ARDL approach. The findings indicate that globalization increases the EF. Different from these results, Apaydin et al. (2021) and Mehmood (2022) conclude that there is no significant relationship between EF and globalization. Some studies, such as Suki et al. (2020) find mixed results in the literature. Suki et al. (2020) show that social and political globalization reduce the EF level, while economic globalization and overall globalization increase the environmental degradation level in the long term for Malaysia over

Table 1 Definitions of variables

Variable	Definition	Measure units	Source
EF	Ecological footprint per capita	Global hectares	Global Footprint Network
GDP	GDP per capita	2010 US dollars	World Bank
KOF	Globalization index	Unitless	Swiss Economic Institute
ENR	Energy consumption	Kg of oil equivalent per capita	World Bank

1970–2018, and the results corroborate the existence of the EKC hypothesis. Ali et al. (2021) test the impact of trade openness and cultural globalization on EF for 128 countries over 1995–2019 regarding the EKC hypothesis. The results indicate that the EKC hypothesis is valid in high-income, lower-middle income, and low-income countries. Besides, findings show that cultural globalization decreases EF in lower-middle and low-income countries while trade openness increases EF in high and low-income countries. Muoneke et al. (2022) test the link between globalization and EF in the Philippines for the period of 1971–2017 using ARDL, FMOLS, and DOLS approaches. The findings reveal that financial globalization has a positive impact on EF, whereas trade globalization affects EF negatively. Radmehr et al. (2022) test the link between globalization and EF in G-7 countries over 1990–2018 using the GMM method. The findings indicate that the impact of financial globalization on EF is negative, while there is no significant relationship between social and economic globalization and EF.

Empirical analysis

Data and model

To examine the EKC hypothesis and the impact of energy consumption and globalization on EF in the EC framework, we use annual balanced panel data for the period 1981–2015 for 26 OECD countries.² The definitions, measure units, and the data source of the variables³ are presented in Table 1. We use EF per capita as a proxy of ecological degradation, GDP per capita as a proxy of economic growth (denoted as GDP), energy consumption per capita (denoted as ENR), and the KOF globalization index (denoted as KOF). EF per capita and KOF globalization

index data are collected from the Global Footprint Network webpage and the KOF Swiss Economic Institute webpage, respectively. GDP per capita and energy consumption per capita data are obtained from the World Bank Development Indicators (WDI).

In order to analyze the EKC hypothesis and the impact of globalization and energy consumption on EF, we use the following log-linear-quadratic function:

$$\ln ef_{it} = \alpha_0 + \alpha_1 \ln gdp_{it} + \alpha_2 \ln gdp_{it}^2 + \alpha_3 \ln kof_{it} + \alpha_4 \ln enr_{it} + u_{it} \quad (1)$$

where $i = 1, 2, 3, \dots, N$ refers the cross-sectional units and t is the time dimension in panel estimation. The α_i indicates the long-run elasticity of corresponding variables.

Empirical methods and results

In this study, to investigate convergence in EF, we employ the club convergence procedure (i.e., “log t regression test”) developed by Phillips and Sul (2007). There are two reasons we follow the log- t test methodology. First, the log- t test is robust for the stationary property of the series because it does not require any particular assumptions about trend stationarity or stochastic stationarity. Second, the log- t regression test resolves the problem of biased and inconsistent estimation resulting from endogeneity and omitted variables in the augmented Solow regression model (Du 2017). Using the Phillips and Sul (2007) methodology, it can be determined whether there is convergence or not. In the case of single factor model:

$$X_{it} = \delta_i \mu_t + \epsilon_{it} \quad (2)$$

where δ_i represents the idiosyncratic distance between the common factor μ_t and the systematic part of X_{it} . The model tries to find to absorb the progression of the individual X_{it} with regard to μ_t via the systematic idiosyncratic element δ_i and the idiosyncratic error (ϵ_{it}) element. Phillips and Sul (2007) extend this model by letting the systematic idiosyncratic element to progress over time, therefore involving heterogeneous individual behavior and progression in that behavior via a time-varying factor loading coefficient δ_{it} . Phillips and Sul (2007) also let δ_{it} to have a random component which absorbs ϵ_{it} and let for possible convergence

² Due to the availability of data, the scope of the analysis is limited to the countries of Australia, Austria, Belgium, Canada, Chile, Denmark, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, Korea Rep., Mexico, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the UK, and the USA.

³ See the Appendix, Table 9 for the descriptive statistics of the variables.

behavior in δ_{it} over time with regard to μ_t . In this case, the model becomes as follow:

$$X_{it} = \delta_{it}\mu_t \tag{3}$$

where δ_{it} and μ_t are time-varying. This time-varying factor model is the decomposition of panel data for a total number of environmental-related patents, (X_{it}), into two components:

$$X_{it} = g_{it} + a_{it} \tag{4}$$

where g_{it} is a systematic component and a_{it} is a transitory component. To set apart common components from idiosyncratic components in the panel, Eq. 1 can be transformed as follows:

$$X_{it} = \left(\frac{g_{it} + a_{it}}{\mu_t} \right) \mu_t = \delta_{it}\mu_t, \text{ for all } i \text{ and } t \tag{5}$$

where μ_t and δ_{it} present the single common component and time-varying idiosyncratic component, respectively. δ_{it} measures the individual economic distance between the μ_t and X_{it} . The number of observations is less than the number of unknowns in the model. As a result, without imposing additional structure on μ_t and δ_{it} , the loading coefficients, δ_{it} , cannot be estimated directly. μ_t might be eliminated by scaling to give the relative loading (or transition) coefficient:

$$h_{it} = \frac{X_{it}}{\frac{1}{N} \sum_{i=1}^N X_{it}} = \frac{\delta_{it}}{\frac{1}{N} \sum_{i=1}^N \delta_{it}} \tag{6}$$

where h_{it} represents the relative transition parameter, which is used to calculate the loading coefficient δ_{it} to the panel average $\frac{1}{N} \sum_{i=1}^N \delta_{it}$ at time t . Equation (3) presents the two properties of h_{it} . First, the cross-sectional mean of h_{it} is equal to one by definition. Second, if the factor loading coefficients δ_{it} converge to δ_t , the relative transition parameter h_{it} will also converge to one. In this case, the cross-sectional variance of the relative transition parameter converges to zero asymptotically in the long run, as shown by Eq. (4). The property $H_t \rightarrow 0$ is used to test the null hypothesis of convergence and to group provinces into convergence clubs.

$$H_t = N^{-1} \sum_{i=1}^N (h_{it} - 1)^2 \rightarrow 0 \text{ as } t \rightarrow \infty \tag{7}$$

To analyze the convergence hypothesis, Phillips and Sul (2007) introduce the following log- t regression model:

$$\log\left(\frac{H_t}{H_r}\right) - 2\log[\log(t)] = \alpha + b\log(t) + u_t \tag{8}$$

for $t = [rt], [rt] + 1, \dots, T$ with $r > 0$

where $[rt]$ represents the initial observation in the regression, indicating that the first fraction of the data is discarded. Phillips and Sul (2007) propose setting $r=0.3$ when the sample is small ($T \leq 50$), based on Monte Carlo simulations. Phillips and Sul (2007) introduce a conventional inferential

Table 2 Log T test results (26 countries)

Variable	Coefficient	Standard error	T -statistic
EF	-0.2571	0.0136	-18.9086

The null hypothesis of convergence is rejected with the T -stats is smaller than -1.65

procedure for Eq. (5). Specifically, they recommend a one-sided t test with heteroskedasticity and autocorrelation-consistent standard errors. The null hypothesis of convergence is rejected if $t_b < -1.65$.

The results in Table 2 indicate that the null hypothesis of full panel convergence in EF is rejected. That is, there is no convergence in the EF values of OECD countries in that period.

Despite the rejection of null hypothesis for the full panel, there may be convergence clubs which converge to different equilibriums. In order to determine possible convergence clubs within the panel, club-clustering procedure is applied. The results show that there are two convergence clubs. Each of these clubs converges to a different constant. The first and second clubs consist of 16 and 10 countries, respectively (Table 3).

Figure 1 reports the relative transition paths of all clubs, which are helpful in comprehending the long-run tendencies between clubs. First of all, we can observe that while club 1 is above the panel mean, which entirely consists of developed countries, club 2 is below the panel average, which includes some developing countries. That is, club 1 and club 2 converge higher and lower EF levels, respectively. These results indicate that developed countries still cause more damage to the environment. Furthermore, we do not observe convergence tendencies between convergence clubs.

Globalization increases socioeconomic interactions between countries. These interactions make it necessary to consider the cross-sectional dependency in panel data models. Besides, each country may have its own characteristics. Therefore, determining whether the slope coefficients are homogenous is also a critical issue in panel data analysis. Ignoring the cross-sectional dependency and the slope homogeneity can cause serious problems, such as inference results, invalid test statistics, and loss of efficiency (Grossman and Krueger 1995; Pesaran and Smith 1995; Coakley et al. 2002; Phillips and Sul 2003; Chudik and Pesaran 2013). Thus, we test the cross-sectional dependency and slope homogeneity to determine the appropriate panel data methods (Table 4).

We employ Pesaran’s (2004) cross-sectional dependence test (CD-test), which is derived from the arithmetic mean of pairwise correlation coefficients of OLS residuals from individual regressions. This test can be applied to spatial panels, balanced and unbalanced panels, and

Table 3 Final club classification

Clubs	Countries	Coefficient	T-statistic
Club 1 [16]	Australia Austria Belgium Canada Denmark Finland France Ireland Israel Korea Rep. Netherlands N. Zealand Norway Sweden Switzerland USA	0.047	3.309
Club 2 [10]	Chile Germany Greece Italy Japan Mexico Portugal Spain Turkey UK	0.321	11.027

The null hypothesis of convergence is rejected with the T-stats is smaller than - 1.65

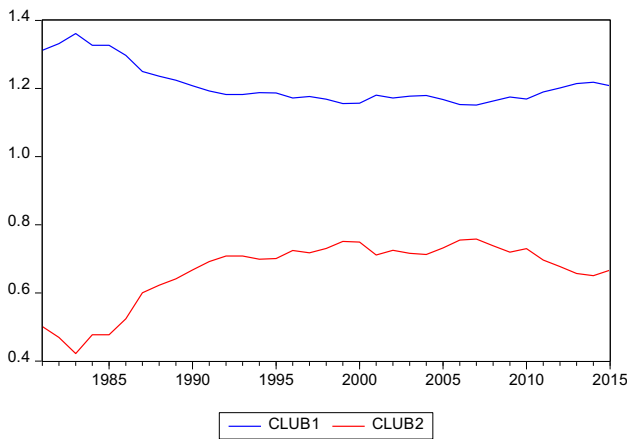


Fig. 1 Convergence clubs

Table 4 Cross-sectional dependency test results

Pesaran CD test		
	Variables	CD
Full panel	lnef	106.005***(0.00)
	lngdp	106.638*** (0.00)
	lnkof	106.627 ***(0.00)
	lnenr	106.622*** (0.00)
Club 1	lnef	64.490*** (0.00)
	lngdp	64.797*** (0.00)
	lnkof	64.799*** (0.00)
	lnenr	64.790*** (0.00)
Club 2	lnef	39.672*** (0.00)
	lngdp	39.681*** (0.00)
	lnkof	39.673*** (0.00)
	lnenr	39.672*** (0.00)

***, **, and * indicate the significance levels at the 1%, 5%, and 10% respectively. The value in the parentheses are P values

dynamic heterogeneous panels with multiple breaks and unit roots (Pesaran 2004). The results indicate that the null hypothesis of the nonexistence of cross-sectional dependence is rejected for all variables in each model. So, there is a strong cross-sectional dependence between countries.

After specifying the cross-sectional dependency, we employ the Pesaran and Yamagata (2008) slope homogeneity test, which is based on Swamy’s test. This test estimates restricted and unrestricted models and compares them. The standard errors for the individual cross-section units are estimated using the weighted fixed effect in the restricted model and the unit-specific estimates of the ordinary least squares estimator in the unrestricted model. This test is dependent on the difference between these two models. If the test statistic is large enough, this means inconsistency between the fixed effects and the unit-specific estimates. Therefore, the null hypothesis of slope homogeneity can be rejected (Pesaran and Yamagata 2008; Bersvendsen and Ditzen 2021). Test results indicate that the homogeneity of slope coefficients is rejected for all models. Therefore, country-specific characteristics should be considered to avoid misleading inferences (Table 5).

To specify the stationary level of the variables, we use Pesaran’s (2007) unit root test, which is based on the augmented Dickey–Fuller (ADF) test. This test allows cross-sectional dependence in heterogeneous panels. The first differences of the individual series and the cross-section averages of lagged levels are used to eliminate the series’ cross-section dependence in this test (Pesaran 2007). The unit root test results reveal that the null hypothesis of non-stationarity cannot be rejected at levels for all variables in both with and without trend models. On the other hand, all the variables become stationary at their first difference (Table 6).

After specifying the stationary level of variables, we use error correction-based Gengenbach et al. (2016) and residual-based Pedroni (2004) cointegration tests, which consider cross-sectional dependency and panel heterogeneity. The null hypothesis of no cointegration is rejected for both tests. That is, all variables are cointegrated for all clubs (Table 7).

Ultimately, we estimated the long-run coefficients through the dynamic ordinary least squares mean group (DOLSMG) method developed by Pedroni (2001). This method is an extended version of the dynamic OLS technique of a single equation to panel data. Cointegrated regression with lead and lagged differences of explanatory variables are augmented to eliminate the endogenous feedback effect in this method (Pedroni 2001; Neal. 2014). It considers the

Table 5 Test for slope homogeneity

	Full panel		Club 1			Club 2	
	Delta	<i>p</i> -value	Delta	<i>p</i> -value	Delta	<i>p</i> -value	
Δ	21.979	0.000	14.470	0.000	14.694	0.000	
Δ_{adj}	22.724	0.000	14.961	0.000	15.192	0.000	

cross-sectional dependency and the panel heterogeneity. The coefficients are estimated by transforming variables by taking the difference from the cross-sectional averages. As can be seen from Table 8, all the estimated coefficients are statistically significant in our model. The findings indicate that GDP per capita has positive and GDP per capita square has negative effects on EF per capita for all clubs and full panel. That is, an inverted U-shaped relationship between GDP per capita and EF exists for both club 1, club 2 and the full panel. These results show that the EKC hypothesis is valid for both clubs, as well as the full panel. These results

are similar to those of Leal and Cardoso Marques (2019), Zafar et al. (2019), and Chen et al. (2020), who find that EKC is valid for OECD countries. However, our result differs from Destek and Sinha (2020), Erdogan and Okumus (2021), and Ng et al. (2022).

The results also indicate that globalization has a positive impact on EF. This implies that globalization gives rise to higher EFs and therefore increases pressures on the ecosystem for all clubs and the full panel. This result is consistent with that of Leal and Cardoso Marques (2019), but inconsistent with those of Zafar et al. (2019), Yang et al.

Table 6 Panel unit root test

		With trend				Without trend			
		Level		First difference		Level		First difference	
		<i>T</i> -bar	<i>P</i> -value	<i>T</i> -bar	<i>P</i> -value	<i>T</i> -bar	<i>P</i> -value	<i>T</i> -bar	<i>P</i> -value
Full panel	lnef	-2.223	0.752	-3.599***	0.000	-1.756	0.53	-3.542***	0.000
	lngdp	-2.111	0.908	-2.787***	0.005	-1.975	0.133	-2.575***	0.000
	lnkof	-2.314	0.559	-3.854***	0.000	-1.896	0.247	-3.419***	0.000
	lnenr	-2.494	0.186	-3.573***	0.000	-1.855	0.323	-3.509***	0.000
Club 1	lnef	-2.321	0.535	-3.838***	0.000	-1.788	0.469	-3.819***	0.000
	lngdp	-1.818	0.991	-2.623 *	0.099	-1.906	0.282	-2.355***	0.009
	lnkof	-2.286	0.597	-3.741***	0.000	-2.042	0.123	-3.290***	0.000
	lnenr	-2.445	0.316	-3.574***	0.000	-1.945	0.228	-3.503***	0.000
Club 2	lnef	-1.959	0.915	-3.207***	0.001	-1.540	0.791	-3.209 ***	0.000
	lngdp	-2.017	0.877	-2.978 **	0.011	-1.554	0.777	-2.650***	0.002
	lnkof	-2.002	0.888	-4.047***	0.000	-1.711	0.592	-3.567***	0.000
	lnenr	-1.984	0.899	-3.144 ***	0.002	-0.871	0.999	-2.940 ***	0.000

***, **, and * indicate the significance levels at the 1%, 5%, and 10% respectively

Table 7 Panel cointegration tests results

	Pedroni cointegration					
	Full		Club 1		Club 2	
	Panel	Group	Panel	Group	Panel	Group
<i>V</i>	1.586	-	1.559	-	0.908	-
<i>Rho</i>	-3.667***	-2.399**	-4.215***	-2.989***	-1.93**	1.345*
<i>T</i>	-8.061***	-8.74***	-8.038***	-8.719***	-4.345***	4.818***
<i>adf</i>	-6.368***	-6.766***	-6.824***	-7.224***	-3.948***	4.9***
GUW cointegration test						
	Full panel	Club 1	Club 2			
Coeff	-1.025	-1.069	-1.112			
<i>T</i> -bar	-4.187	-4.501	-5.071			
<i>p</i> -value	≤0.01	≤0.01	≤0.01			

***, **, and * indicate the significance levels at the 1%, 5%, and 10% respectively

Table 8 DOLSMG results

	Full panel DOLSMG	Club 1 DOLSMG	Club 2 DOLSMG
lngdp	3.411*** (0.000)	2.112** (0.000)	2.031*** (0.000)
lngdp2	−0.135** (0.033)	−0.109*** (0.000)	−0.102*** (0.000)
lnkof	0.392*** (0.000)	0.121** (0.018)	0.826*** (0.000)
lnenr	1.12*** (0.000)	0.297*** (0.000)	0.683*** (0.000)

***, **, and * indicate the significance levels at the 1%, 5%, and 10% respectively. The value in the parentheses are *P* values

(2021), Chen et al. (2020), and Erdogan and Okumus (2021). According to the results, a 1% increase in the KOF index approximately increases EF by 0.4%, 0.1%, and 0.8% for the full panel, club 1, and club 2, respectively. That is, the impact of globalization on EF is higher for club 2, which includes developing countries. As Copeland and Taylor (2004) pointed out, globalization causes the establishment of pollution-intensive industries in developing countries due to their weak institutional structures.

According to the results, a 1% increase in energy consumption approximately increases EF by 1.1%, 0.3%, and 0.7% for the full panel, club 1, and club 2, respectively. These results reveal that the transformation in the use of renewable energy has not yet been achieved. On the other hand, the estimated coefficients are smaller for club 1. These findings indicate that club 1 countries have more environmentally friendly energy policies. When the countries in the clubs are considered, it is striking that developing countries such as Chile, Turkey, Mexico, and Portugal are in the second club. As these countries are in relatively earlier stages of development, the income per capita level is relatively low. While these countries primarily focus on economic growth and employment by taking advantage of opportunities such as international investment and trade that increase with globalization, the prevention of environmental degradation remains in the background. Therefore, the coefficients of globalization and energy consumption are higher as expected. On the other hand, as per capita income increases, environmental awareness can increase, and cleaner policies can be followed in these countries.

Conclusion and policy implication

Global efforts to reduce the damage caused by humanity to the environment, especially GHG emissions, are increasing. One of the most important of these efforts is to target

convergence in pollution, which is essential in terms of equality and fairness since the damage caused by countries to the environment differs significantly. Therefore, this heterogeneity between countries should be considered in econometric analyses.

Within this motivation, in this study, we analyze the role of globalization in EF and test the existence of the EKC hypothesis for OECD countries over the period 1981–2015. To do so, we follow a different path from the existing literature. We first identify EF convergence clubs using the non-linear factor model introduced by Phillips and Sul (2007). Afterward, we examine the impact of globalization on the EF for all convergence clubs within the framework of the EKC hypothesis. The club convergence test results show two convergence clubs, each converging to a different state. While club 1, which converges to higher ef levels and includes 16 developed countries, club 2, which converges to lower EF levels, includes 10 countries and some of which are developing countries. The results show that the EKC hypothesis holds for both convergence groups. However, the impact of globalization and energy use on the EF is higher for club 2, which mainly includes developing countries.

These results show that a different approach should be put forward in international negotiations on the environment. The EF levels are still higher in developed countries in OECD. On the other hand, globalization has negative effects on the environment for all countries, but these effects are more harmful to developing countries. In order to eliminate the negative effects of globalization on the ecosystem and ensure humanity's sustainable development, it is necessary to give globalization a new direction. Besides, relatively more polluted energy is used in developing countries. Determining the same target for each country creates negativities regarding applicability, fairness, and equality. Instead, a rapid transition period should be identified for developing countries at a relatively early stage of industrialization. In addition, financial and technical support should be provided to these countries to use cleaner energy in this process. However, in order to limit global warming to 1.5°, countries should take measures in cooperation as soon as possible. Moreover, there are also other environmental problems that urgently need to be resolved by implementing common policies. Therefore, new commitments should be determined for all countries to not only reduce CO₂ emissions but also solve the other environmental problems urgently, and all nations must immediately start implementing policies in line with these new commitments. The following policies can be effective in reducing environmental pollution: more efficient use of energy, investment in renewable energy sectors, increasing support for financing these investments and supporting research and development studies in these sectors, levying pollution taxes on the pollutant or action causing the environmental damage, implementing effective policies to increase environmental awareness.

Appendix

Table 9 Descriptive statistics

	Variable	Obs	Mean	Std. Dev	Min	Max
Full Ppanel	EFC	945	5.70	1.75	2.06	10.48
	GDP	945	33,757.98	16,746.82	3884.62	91,565.73
	KOF	945	72.26	14.40	25.60	90.966
	ENR	945	3766.86	1760.39	704.79	8455.55
Club 1	EFC	595	6.47	1.56	2.32	10.48
	GDP	595	39,821.46	16,097.66	3884.62	91,565.73
	KOF	595	74.74	14.25	25.60	90.66
	ENR	595	4524.38	1654.49	1046.41	8455.55
Club 2	EFC	350	4.40	1.21	2.06	6.90
	GDP	350	23,450.08	12,178.28	4465.63	47,102.58
	KOF	350	68	13.67	25.89	89.10
	ENR	350	2479.07	1040.14	704.79	4629.18

Author contribution Volkan Bektaş: conceptualization, data curation, methodology, software, writing—review and editing. Neslihan Ursavaş: methodology, software, writing—review and editing.

Data availability The data underlying this article are available at: <https://data.worldbank.org/>
<https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html>
<https://data.footprintnetwork.org>

Declarations

Ethics approval Hereby, we consciously assure that the following is fulfilled for this manuscript:

- This article does not contain any studies involving humans or animals performed by any of the authors.
- This paper is the authors' own original work, which has not been previously published elsewhere.
- The paper is not currently being considered for publication elsewhere.
- The paper reflects the authors' own research and analysis in a truthful and complete manner.
- The paper properly credits the meaningful contributions of co-authors and co-researchers.
- The results are appropriately placed in the context of prior and existing research.
- All sources used are properly disclosed (correct citation).
- All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Competing interests The authors declare no competing interests.

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