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# **New insights on the environmental Kuznets curve hypothesis in developing and transition economies. A literature survey**

Alexandra-Anca PURCEL\*

Babeş-Bolyai University, Faculty of Economics and Business Administration, Teodor Mihali St.  
58-60 400591, Cluj-Napoca, Romania  
Université Clermont Auvergne, CNRS, IRD, CERDI, F-63000 Clermont-Ferrand, France

\*Corresponding author: [alexandra.anca.p@gmail.com](mailto:alexandra.anca.p@gmail.com)

**Abstract:** We perform an updated literature survey on pollution-growth nexus via the Environmental Kuznets Curve (EKC) hypothesis, both from theoretical and empirical standpoints. First, we conduct a literature review on the most well-known rationale behind the EKC prevalence and discuss the key components of the research design when estimating the EKC. Second, we bring together the most influential empirical papers published in the last decade, which focus on EKC estimation in developing and transition economies. Overall, succeeding to curtail some of the deficiencies suggested by theoretical contributions, the recent empirical studies might indicate a certain consensus regarding pollution-growth nexus, and EKC validity. On the one hand, reinforcing the EKC nature, several studies reveal a long-run relationship between indicators. On the other hand, according to income coefficients signs, the traditional bell-shape pattern seems to be at work for some developing and transition economies. However, in some cases, the estimated turning point lies outside the income sample range, calling into question not only the true pattern between pollution and growth but also the identification of EKC. Taken collectively, both the theoretical foundations and empirical evidence, could contribute to a better understanding of the pollution-growth nexus in the EKC context, and suggest some useful insights regarding the future works on the subject as well as the crucial policy implications in this group of countries.

**Keywords:** environmental Kuznets curve hypothesis; developing and transition economies; literature survey.

**JEL Classification:** Q53, Q56, Q43.

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## **I. Introduction**

Recently, one of the major concerns of nations has become global warming, and particularly the adverse effects that this phenomenon produces on Earth and implicitly on the quality of life. Along with the start of the Industrial Revolution, there are significant changes at the global level, both economically and socially, which also reflects on the environment.

As an answer to the concerns related to environmental degradation-economic growth nexus, and the desire to synthesize them into a general mission of the population and the competent bodies, the World Commission on Environment and Development (1987) in the report entitled *Our Common Future* (i.e. Brundtland Report), shaped the definition of sustainable development. According to this publication, "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations General Assembly, 1987, p. 41)<sup>1</sup>. Indeed, this may not be the first and the perfect attempt to define what sustainable development constitutes, but we surely can argue that is one of the most used and debated explanation in the related literature (see e.g. Seghezzeo, 2009; Ciegis et al., 2009; Stoddart, 2011; Holden et al. 2014, among others). Furthermore, if we look back in history, before the Brundtland report, Malthus (1798), in his book "Essay on the Principle of Population" outlines some important future changing in nations' economic structure. He argues that the world's population grows at a geometric rate while the food supply increases at an arithmetic rate, leading over time to exhaustion of natural resources. Later, a report writes by Meadows et al. (1972), and suggestively named "The Limits to Growth" brings to light the same issues related to the excessive increases in population and economy due to industrial expansion, while natural resources follow a downward trend. Authors such as Basiago (1999) and Sandmo (2015) highlight the importance of these two studies as fundamental pillars in the development of environmental and energy economics as an autonomous field.

Consequently, the importance of awareness of environmental protection and its interdependence with specific indicators at the macro- and micro-economic level have become an important topic in the early literature. Besides, along with the development of new theoretical concepts, more and more empirical studies have begun to emerge. Nowadays, as a result of the

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<sup>1</sup> <https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf>

increase in data availability and the development of more sophisticated statistical techniques, there is a substantial flow of research papers related to the field of environmental and energy economics.

This study aims to review in an integrated framework the key theoretical aspects and give an updated empirical overview of the relationship between environmental degradation and economic growth via the Environmental Kuznets Curve (hereafter EKC) hypothesis. In doing so, first, we tackle the theoretical knowledge regarding the EKC, by stating the most well-known rationales behind its prevalence. Next, we move across towards the research design in terms of EKC testing and provide some details about its fundamental components, namely the model specification, assumptions, econometric methodology, and identification strategy. Second, we survey the empirical papers published in the last decade (i.e. from 2010 to 2019) that focus on developing<sup>2</sup> and transition economies and investigate the validity of the EKC hypothesis. Therefore, comprising together the latest published research, we would have a more homogeneous picture of the EKC literature. Moreover, along with the rapid development of more advanced statistical techniques and the increase in data availability and quality, the EKC testing approaches have also changed (Dasgupta et al., 2002; Lieb, 2003). As such, we are inclined to believe that, on the one hand, the recent studies are more accurate vis-à-vis the research design, while, on the other hand, the increased data quality has improved the prediction of EKC both in terms of parameters and turning point estimates. Relying on this intuition, and opposite with the review of He (2007), who targets the SO<sub>2</sub> EKC hypothesis for the developing and transition economies and Shahbaz and Sinha (2019), who concentrate on the CO<sub>2</sub> EKC hypothesis, we survey the papers independent of pollution indicator used in EKC testing. Also, compared to the survey of Tiba and Omri (2017) on the relationship between energy, environment, and growth, we focus solely on the EKC hypothesis works and provide an updated review of the related literature.

Our findings are as follows. First, several studies reveal a long-term relationship between environmental pollution and income. Thus, the long-run character of EKC seems to prevail and strengthen the belief that the EKC is rather a phenomenon that may be observed over a relatively long period, all the more that the effects of environmental policy are visible after years from implementation. Second, it is encouraging to see that the bell-shape pattern between pollution and growth seems to emerge frequently for some developing and transition states—perhaps contrary to the general intuition that it is more challenging for these countries, compared to developed ones,

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<sup>2</sup> In this paper, the term "developing" refers to both developing and emerging economies.

to reach the optimal level of growth that could ensure the decline of pollution level, i.e. inducing an upward bending curve. Overall, this may suggest that less-developed nations might improve their environmental quality by avoiding and learning from the mistakes made by developed countries, and even switch pollution trends in favor of the environment for a lower income level (Munasinghe, 1999; Dinda, 2004; Yao et al., 2019). However, the mixed results are expected when spanning different periods and using different pollution indicators, even for the same country or group of countries. Third, in some cases, the estimated turning point lies outside the income sample values. As such, this may imply, on the one hand, a possible monotonically increasing pattern between indicators (see e.g. Cole et al., 1997; Stern and Common, 2001; Lieb, 2003) and, on the other hand, might reveal potential weaknesses in the identification of EKC (see e.g. Bernard et al., 2014). Regarding the latter, it becomes imperative for the researcher to determine the minimum set of assumptions to identify the genuine causal effects between variables and if we refer to the parametric approach to identify the parameters point estimate. Also, a broader perspective in terms of the statistical methods may provide further insights into EKC and narrow some of the related uncertainties. In this fashion, the methods designed to minimize the model assumptions, such as semi-, and non-parametric techniques<sup>3</sup>, along with the ones that go beyond the time-domain approach, such as wavelet techniques related to the time-frequency domain, may provide a sound basis of comparison for the traditional econometric tools, or vice-versa (i.e. parametric methods should be seen as complementary to these methods). Ultimately, a valuable alternative to achieve robustness is when the results of different techniques incline, more or less, towards the same conclusion. For example, based on our short nonparametric descriptive exercise, China exhibits an increasing pattern between CO<sub>2</sub> and GDP, a result also suggested by several time-series and panel studies included in our empirical review—although the sign of the associated income coefficients indicate a bell-shape pattern, some studies find turning points that lie outside the income sample range, thus, indicating a positive relationship<sup>4</sup>.

The rest of the paper is organized as follows. Section 2 discusses the theoretical arguments that constitute the basis of the bell-shaped pattern between pollution and economic growth, Section

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<sup>3</sup> It is worth mentioning that we do not argue that this type of analysis should be performed instead of a parametric one, or provide better results at the advantage of fewer assumptions.

<sup>4</sup> We take China as an example since a large number of studies considered focus on testing EKC for this country, compared to other states. However, a comparison could be made for the other states as well. Besides, we look for an overall behavior independent of the period analyzed, pollution indicator, and empirical methodology.

3 explores the potential patterns between CO<sub>2</sub> emissions and economic growth descriptively, Section 4 reviews the empirical studies on EKC, and Section 5 concludes and provide some policy implications.

## **II. Theoretical aspects of EKC**

Presumably, one of the most tested hypotheses in the literature that stresses the relationship between environmental degradation and economic growth is the EKC hypothesis. The assumption that the link between pollution and economic growth follows a bell-shape pattern is first introduced in the literature by Grossman and Krueger (1991). In their seminal paper, the authors analyze the implications that the North American Free Trade Agreement (NAFTA) has on the environment through the medium of economic growth. Based on the empirical findings, they conclude that the form of the relationship between economic growth and environmental degradation is inverted U-shaped. Thus, the quality of the environment tends to deteriorate along with economic growth until an income threshold is reached, from which the trend is reversed in favor of the environment. Approximately during the same period, Shafik and Bandyopadhyay (1992) and Panayotou (1993) also search into the implications of economic growth on the environment, while the latter named the relationship between these two macro-indicators the EKC.

### *2.1. The rationale behind the EKC hypothesis*

Throughout the years, the number of studies that have approached both theoretically and empirically the EKC hypothesis and its extensions have increased considerably. Most researchers have tried to answer the following question: Which are the drivers that shape the relationship between environmental degradation and economic development? Some authors provide potential explanations based on economic intuition. In contrast, others develop well-grounded theoretical models around a series of assumptions and/or restrictions which at least theoretically generate a bell-shaped pattern between pollution and economic growth. In the following, we look at some well-known rationale behind the EKC hypothesis provided by the existing literature, from both the side of economic intuition and theory, and briefly discuss them.

First, Grossman and Krueger (1991) argue that the scale, structural, and technological effect may explain the nexus between pollution and growth. The scale effect manifests as a result

of economic activity expansion, which in turn induces a rise in the pollution levels. In contrast, structural or compositional effect accounts for the structural changes that take place within the economy. Furthermore, once nations attain industrial apogee, they focus more on the development of information-based industries and services. Thus, as a state becomes intensive in services, it ensures a higher economic growth rate, and eventually, a steady decline in environmental degradation. Besides, in the post-industrial phase, countries have the necessary resources to invest in research, development, and innovation programs, and due to technological advancement, old technologies are gradually replaced with more efficient and less polluting ones (Panayotou, 1993, 2003).

Second, the nation's economic development also implies an increase in the population income. As such, if the quality of the environment is regarded as a normal good, its demand may be influenced positively. In the related literature, some researchers have empirically confirmed the presumption that environmental quality is a normal good (see e.g. Kristrom and Riera, 1996; Bruneau and Echevarria, 2009; Martini and Tiezzi, 2014), while researchers such as Pearce and Palmer (2005) and Ghalwash (2007) have argued that the quality of the environment is more a luxury good. Consequently, the soundness of the EKC hypothesis may be a consequence of these fluctuations in the income elasticity of demand for environmental improvement.

Third, along with the rise in income, the individual's perception of the adverse effects of environmental degradation on quality of life also increases. As an overall outcome, compared to poorer countries, developed states tend to adopt more stringent environmental policies and regulations. Hence, in developing states, environmental regulations are fewer, and they are prone to become pollution havens for dirty industries that migrate from developed ones (Lucas et al., 1992). Also, authors such as Stern et al. (1996), Suri and Chapman (1998), and Stern (2003), among others, advocate that the bell-shaped pattern for developed nations may be explained through the implications of trade. Moreover, researchers such as Dasgupta et al. (2002), among others, argue that improvements in environmental quality are possible even in developing countries. Besides, the pollution may follow a downward trend for a lower level of income than those experienced by developed countries, considering the increase in the availability and novelty of methods to combat pollution.

Fourth, in the early literature, some authors provide theoretical models that attempt to explain the EKC behavior. In this fashion, some of these early theoretical works are discussed in

the well-know study of Stern (2004). Likewise, more recently, Kijima et al. (2010) provide a comprehensive and valuable survey on both theoretical static and dynamic models behind the EKC hypothesis with detailed mathematical explanations, along with a review on empirical analysis. In Table 1, we summarize these theoretical contributions concerning the EKC hypothesis as they appear in Kijima et al. (2010).

**Table 1.** Theoretical studies on EKC based on Kijima et al. (2010)

<i>Static models</i>	
Model type	Authors
Models with macroeconomic production functions	Lopez (1994), Lopez and Mitra (2000).
Models with utility functions only	McConnell (1997), Andreoni and Levinson (2001), Lieb (2002), Di Vita (2004).
<i>Dynamic models</i>	
Resource allocation	John and Pecchenino (1994), John et al. (1995), Selden and Song (1995), Lieb (2004), Dinda (2005), Chimeli and Braden (2008), Prieur (2009).
Technology and resource selection	Stokey (1998), Hartman and Kwon (2005), Tahvonen and Salo (2001).
Tax policy	Jones and Manuelli (2001), Egli and Steger (2007).
Real options approach	Wirl (2006), Kijima et al. (2011).

In addition to this theoretical works, Brock and Taylor (2010) taking stock of the earlier theory literature (e.g. Stokey, 1998), establish the EKC hypothesis-Solow model nexus. In their seminal contribution, the authors use the underlying assumptions of the well-known neoclassical growth model introduced by Solow (1956) and account for environmental pollution in the main equation of the Cobb-Douglas production function. As such, they developed a new model (i.e. Green Solow model) which provide a theoretical setup that may explain the bell-shaped pattern between pollution and economic growth through the same forces that assure the course of economic growth, namely the law of diminishing returns and the advancement of new technology (Brock and Taylor, 2010). Subsequently, as Kijima et al. (2010) argue, the Green Solow model is "a macroeconomic dynamic model in which total production is allocated to consumption and abatement expenditure" (Kijima et al., 2010, p. 1193). Indeed, the Green Solow model is a simple dynamic model that may give a strong rationale behind the EKC hypothesis, and an adapted empirically testable convergence equation for emissions per capita.

Conversely, Ordás Carido et al. (2011) further develop the Green Solow model and provide a theoretical framework in which the reduction in pollution is endogenously determined. In particular, the theoretical predictions formulated by authors suggest that through the scale (defensive) effect, the growth rates in pollution are associated positively (negatively) with GDP



growth (emissions levels). Next, using convergence-type equations estimated based on three different econometric approaches (i.e. parametric, semi-, and non-parametric), the authors show that the data validate both the scale and defensive effect. Besides, the possible reverse causality between pollution and growth implied by the theoretical model is addressed empirically by employing instrumental variables. Overall, the empirical findings suggest that the more flexible specifications (semi-, and non-parametric) are preferred when modeling the data, compared with the classical parametric ones. Moreover, opposed to Brock and Taylor (2010), who link CO<sub>2</sub> emissions (a global stock pollutant) with economic growth, the theoretical model introduced in Ordás Carido et al. (2011) is designed for local flow pollutants, such as SO<sub>2</sub> and NO<sub>x</sub> emissions.

In this sub-section, we review some notable empirical and theoretical works that target the pollution-growth nexus and seek directly, or at least indirectly, into the rationale that may explain the bell-shaped pattern between the indicators. However, as also suggested by these studies, the reasons behind the validity of the EKC hypothesis are more diverse, and in the related theoretical and empirical literature, the views are also mixed. Among the researchers who provide literature surveys, critics and search into the rationale of EKC hypothesis, we mention the works of Stern et al. (1996), Borghesi (1999), Lieb (2003), Dinda (2004), Stern (2004), He (2007), Carson (2009), Bo (2011), Pasten and Figueroa (2012), Kaika and Zervas (2013a), Kaika and Zervas (2013b), Stern (2015), and Tiba and Omri (2017).

## *2.2. Model specification, assumptions, econometric methodology, and identification strategy*

### *2.2.1. Model specification*

The classical and probably the most used empirical strategy to model the link between environmental degradation and economic growth is through the polynomial equations of the second-, and third-degree (see e.g. Grosman and Krueger, 1991; Panayotou, 1993; and the more recent studies of Miyama and Managi, 2014; Lazăr et al., 2019; Chen et al., 2019b; among others). The use of quadratic function allows testing the traditional EKC hypothesis (i.e. the potential bell-shaped pattern between pollution and growth), while the specification of a higher polynomial order, such as the cubic function, allows the representation of multiple patterns. These patterns cover the N-shape (a potential extended EKC when the coefficient of income, squared income and cubic income is positive, negative and positive, respectively, and statistically significant), the traditional bell-shape pattern (the coefficient of income and squared income is positive and

negative, respectively, and statistically significant), and also a monotonic increasing (decreasing) relationship when only the income coefficient is statistically significant and positive (negative). Indeed, modeling the EKC through the parametric approach implies that the functional form and also the distribution is already assumed<sup>5</sup> (Miyama and Managi, 2014). Thus, for example, an imposed shape of the relationship through the introduction in the equation of a squared or cubic income term, when the relationship is linear, could induce weak identification, and also could bias the turning point (Bernard et al., 2014). However, to reduce the bias that may potentially arise from imposing a specific functional form, econometrically one may (i) assume the largest polynomial, i.e. cubic specification, and estimate sequentially also the quadratic and linear equation to show consistency in coefficients significance (for example, if the income terms are statistically significant in a third-order polynomial equation, intuitively in the second-order polynomial equation they should lack statistical significance; see e.g. Lazăr et al., 2019), (ii) use specific tests for the presence of a potential nonlinear relationship (see e.g. Lind and Mehlum, 2010), or (iii) employ simultaneous with the parametric techniques also the semi-, and non-parametric alternatives to assure robustness, or at least to deduce a pattern between variables descriptively (see e.g. Millimet et al., 2003; Ordás Criado et al., 2011; Bernard et al., 2014; among others). Besides, it is worth noting that not only the results obtained for the income coefficients signs, but equally, the presence or absence of a turning point helps in determining the pattern followed by the data.

A second strand of studies (see e.g. Millimet et al., 2003; Tsurumi and Managi, 2010a, 2010b; Ordás Criado et al., 2011; Chen and Chen, 2015; Sen et al., 2016; Zhang et al., 2017; Luzzati et al., 2018; among others) have challenged the classical parametric approaches, which most are based on an imposed order for the polynomial equation, by estimating the pollution-income nexus using more flexible empirical strategies, such as semi-, and non-parametric methods. In this regard, the findings of Millimet et al. (2003) and Ordás Criado et al. (2011) show that compared to parametric counterparts, the semi-, and non-parametric alternatives are preferred when modeling the data. Although the amount of semi- and non-parametrical EKC literature has increased over the years, it remains relatively low compared to parametric one. First, one of the reasons may be related to the well-known curse of dimensionality issues in fully nonparametric

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<sup>5</sup> Also, the parametric quadratic function implies symmetry since, at both sides of the threshold, the pollution increases and decrease by the same rate.

models, induced when many factors are included in the equation. Bearing in mind a crucial and well-debated econometric objection about EKC, namely the omitted variable bias (see e.g. Stern, 2004), there is a need to account for at least the most influential factors of pollution along with the income (e.g. energy consumption, trade, foreign direct investments, structure of economy, globalization, economic freedom—to mention just a few of them), to obtain reliable and consistent results. Consequently, the curse of dimensionality could be a plausible impediment in applying nonparametric methods, but it can also be alleviated by working with semi-parametric methods. Second, the graphical representation results of semi- and non-parametrical models may be more complex and harder to interpret, thereby most researchers seem to prefer more straightforward results, such as point estimates. Third, the insufficiency of clear-cut statistical inference procedures in the nonparametric field could influence its soundness and applicability. Forth, usually in economics and also in energy and environmental economics sub-fields, the vast majority of studies rely on some theories or prior empirical evidence. Therefore, in most cases, the specification of the model is already predefined. Furthermore, these theories and empirical regularities—some of the well-known mentioned in the above sub-section, come along with different (parameters) assumptions and/or restrictions, which may be more convenient to address through parametric techniques. Some of these possible deficiencies of semi-, and non-parametric models are also acknowledged in the context of EKC estimation by authors such as Tsurumi and Managi (2010a) and Bernard et al. (2014), among others.

### 2.2.2. Model assumptions and econometric methodology

Although in the last two decades, some theories regarding the validity of EKC have emerged in the literature, the vast majority of the studies rely mostly only on econometric assumptions and/or restrictions (e.g. exogeneity, long-, and/or short-run homogeneity and heterogeneity, order of integration—for the independent factors; equal variance, lack of autocorrelation, normality—for residuals; persistence, order of integration—for endogenous variable; among others), in modeling the relationship between pollution and economic growth.

On the one hand, the potential econometric issues (e.g. cross-sectional dependence; times-series properties, such as stationarity and cointegration; endogeneity bias caused by simultaneity, omitted variables, models misspecification, dynamic endogeneity or data measurement errors; among others) that can arise in estimating the pollution-growth nexus and produce biased

estimates, if they are neglected, could be reduced by considering a (minimum) set of assumptions. However, it is generally acknowledged that both the data and sample characteristics play an essential role in dictating the choice of the most appropriate model specification and also the optimum econometric strategy. For instance, in testing EKC, the parameters homogeneity assumption in panel data models may be too restrictive, and the overall results may not describe the real general or individual pattern for each panel member (see e.g. Stern, 2010; Kaika and Zervas, 2013). Therefore, if the turning point occurs at the panel level, the behavior does not need to be preserved at the country-level, and the turning point could be well above the observed income values. As Bernard et al. (2014) point out, when working with a panel composed of different countries, disaggregation may be a valid solution to mitigate the bias of data pooling.

In the view of the previous, recent studies, such as Barra and Zotti (2017), illustrate for a sample of 120 countries spanned over 2000-2009 that once considering the nonstationarity property of the data, the evidence of an inverted U-shape relationship between CO2 emissions and GDP vanishes in favor of a monotonic increasing one. Besides, to overcome the different sample composition issues, the authors eliminate alternatively from the sample the same geographical region and income distribution states. Overall, the estimates suggest that the sample composition reshapes the main findings. Furthermore, Miyama and Managi (2014), among others, suggest that excluding low-income countries from analysis due to data availability may alter the results. As such, to deal with missing data problems and its undesirable consequences on EKC estimation, they propose a series of imputation methods. Also, Stern and Common (2001) suggest that the inclusion or exclusion of developing states from the analysis may influence the occurrence of a turning point.

On the other hand, the development of novel panel<sup>6</sup> estimators that allow for different long- and short-run slope assumptions (see e.g. the panel ARDL technique with the associated Pooled Mean-Group, Mean-Group, and Dynamic Fixed Effects estimators discussed in Pesaran et al., 1999), which are also robust to various potential econometric problems, such as the different order of integration for regressors and variables cointegration (see e.g. Pesaran and Smith, 1995; Pesaran, 2006; Eberhardt and Bond, 2009; Eberhardt and Teal, 2010), cross-sectional dependence

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<sup>6</sup> We discuss here some of the recent developments of panel data techniques, as panels include both N and T dimensions, and the EKC is usually tested using panel data models. Still, it is worth mentioning that the advanced in the time-series econometric tools are more or less similar.

(see e.g. Pesaran, 2006; Eberhardt and Bond, 2009; Eberhardt and Teal, 2010; Chudik and Pesaran, 2015; Chudik et al., 2016), and endogeneity (see e.g. Pesaran et al., 1999; Chudik and Pesaran, 2015; Chudik et al., 2016), facilitate the EKC estimation. Besides, the preliminary analysis techniques, such as stationarity and cointegration tests, have also been developed to deal with cross-sectional dependence, parameter heterogeneity, among other potential econometric issues. Nonetheless, taking note of the aspects mentioned above is ultimately the task of the researcher to properly formulate the set of assumptions and adapt the methods to sample particularities.

### 2.2.3. Identification strategy

The assumptions and restrictions consider by the researcher help in shaping the proper identification strategy and inference. In the light of previous EKC literature, which provides no consensus on its validity and the associated turning point, the recent landmark study of Bernard et al. (2014) waves a red flag regarding the weak identification of both EKC and the related turning point. More specifically, the authors investigate the estimation precision of the EKC turning point using Delta and Fieller method, while controlling for a wide set of potential econometric issues (i.e. endogeneity, persistence, and functional form). The overall findings show that the estimation of the EKC turning point lacks precision (i.e. the associated confidence intervals are very large) and, thus, the policy implications based on EKC may be altered. However, the results suggest that precision is higher when considering local pollutants, a long-term perspective, or nonparametric alternatives.

In the same manner, few years before the study of Bernard et al. (2014), the seminal work of Wagner (2008) and Vollebergh et al. (2009) highlights some of the most prominent weaknesses of EKC econometrics since its grounding, and raise the relevance of its identification, respectively. On the one hand, Wagner (2008) discusses two econometric issues that lately have governed the panel data EKC literature, namely the stochastic properties of nonlinear terms of integrated variables and the cross-sectional dependence. In particular, the author shows that employing standard nonstationary panel data techniques, which do not take into account the nonlinear transformations of integrated variables and cross-sectional dependence, the bell-shaped pattern between emissions and income holds. However, when using stationary de-factored data to deal with the problems mentioned above and appropriate estimation techniques, the EKC hypothesis seems to be invalidated (all the more, these findings are robust for a comprehensive set of tests,

and when the poolability assumption is relaxed). The estimations are conducted on a reduce model between CO<sub>2</sub> (SO<sub>2</sub>) and GDP for a panel of 100 (97) countries spanned over the period 1950-2000.

On the other hand, Vollebergh et al. (2009) go beyond the standard econometric issues and emphasize the relevance of a proper identification strategy as a starting point in investigating the reduced form pollution-income nexus in panel data. Considering that one can distinguish between the impact of income and time effects on pollution, the authors argue that countries alike are characterized by identical time effects. Accordingly, the corroborated estimates of the income and time effects on CO<sub>2</sub> and SO<sub>2</sub> emissions for 24 OECD countries over the period 1960-2000, based on the pairwise differencing technique, show that the bell-shape pattern holds only SO<sub>2</sub> emissions (i.e. a locally regulated pollutant). Overall, the work of Vollebergh et al. (2009) may suggest that imposing different identifying restrictions for the exogenous variable (income) and control variable (time) yield to different model specifications, and in turn, to different findings regarding the pollution-income patterns. Besides, the authors establish a solid link between the theoretical models on EKC (see e.g. Brock and Taylor, 2005, 2010; Ordás Criado et al., 2011), and the minimal set of requirements needed for the identification of pollution-income nexus in EKC context.

In addition, Stern (2010) addresses both the issues pointed by Wagner (2008) and Vollebergh et al. (2009), namely the higher-order terms of integrated income variable, the cross-sectional dependence, and the identification of income and time effects in EKC reduced models, through the between estimation technique. Using the same datasets for CO<sub>2</sub> and SO<sub>2</sub> emissions as Wagner (2008) and Vollebergh et al. (2009), the author shows that overall the results do not validate the traditional EKC hypothesis. In the same vein, the study of Stern et al. (2017) consider both the problems raised by Wagner (2008) and Volleberg et al. (2009) and also the omitted variable bias of between estimator employed in Stern (2010). As such, to mitigate their related undesirable effects on EKC results, the authors suggest working to long-run growth rates of pollution and income variables, while adding additional factors to account for the variation around the trend. The findings indicate that the EKC is not at work both for the full sample of CO<sub>2</sub> and SO<sub>2</sub> emissions. Moreover, Sen et al. (2016) use a slightly modified identification strategy for income and time effects, based on the pairwise differencing approach as Vollebergh et al. (2009), and further control for the potential issues caused by nonstationarity, employing nonlinear

nonstationary parametric and nonparametric techniques. The overall findings indicate that the time effects do not have the power to detract the positive income effects, pointing out that the regional CO<sub>2</sub> EKC hypothesis is not at work for the period 1950-2010.

Here we discussed some of the latest most influential studies that couple the EKC with the relevance of identification procedures. The general idea of these studies lies in the fact that a large part of the empirical EKC literature lacks in providing a (reasonable) identification strategy, which reflects in misleading findings concerning its validity and the computation of associated turning point. Consequently, the identification of the pollution-growth nexus should not be "taking as is given", but rather assembled through convincing assumptions and investigated using appropriate econometric tools.

### **III. CO<sub>2</sub> emissions stylized facts: a short descriptive empirical exercise**

Clear evidence of deterioration in the quality of the environment is the sharp increase in greenhouse gas (GHG) emissions following human activities, in the post-industrial period, compared to the levels recorded prior to it. Also, CO<sub>2</sub> is considered to be the greatest environmental threat, given the rapidity that its concentrations have increased over the years. During the pre-industrial period, the atmospheric CO<sub>2</sub> concentration resulting from the combustion of fossil fuels is about 280 parts per million (ppm)<sup>7</sup>, while in 2016, it reaches about 403 ppm, on average. Put differently, due to fossil fuel combustion and cement production, in 2016, the atmospheric CO<sub>2</sub> is 145% above pre-industrial levels (see World Meteorological Organization, 2017)<sup>8</sup>.

Moreover, the CO<sub>2</sub> emissions account for 72% of global GHG emissions in 2016, while 50% of this CO<sub>2</sub> emissions come from electricity and heat production together with the industry sector. According to Olivier et al. (2017), the top six CO<sub>2</sub> emitters in 2016 are China, the United States (US), India, the Russian Federation, Japan, and the European Union(28) (EU28), being responsible for approximately 68% and 63% of total global CO<sub>2</sub> and total GHG emissions, respectively. However, in 2016, the CO<sub>2</sub> emissions decline in the Russian Federation (-2.1%), US (-2.0%), Japan (-1.2%) and China (-0.3%), while an increase is registered in India (4.7%) and the EU(28) (0.2%) (Olivier et al., 2017). Besides, the CO<sub>2</sub> emissions are just an example of an air

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<sup>7</sup> =number of molecules of the gas per million (10<sup>6</sup>) molecules of dry air.

<sup>8</sup> [https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/GHG\\_Bulletin\\_13\\_EN\\_final\\_1\\_1.pdf?LGJNmHpwKkEG2Qw4mEQjdm6bWxgWAJHa](https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/GHG_Bulletin_13_EN_final_1_1.pdf?LGJNmHpwKkEG2Qw4mEQjdm6bWxgWAJHa)

pollutant that contributes to the degradation of the environment, but the spectrum is much broader (e.g. air, water, land, noise, and light pollutants). Indeed, a vast majority of empirical studies have used CO2 emissions as a proxy for environmental degradation (see e.g. Table 2 and Table 3 in the next section). Perhaps, its importance to climate change and data availability have determined the researchers to focus more on its related impacts, in comparison to other types of pollutants.

Consequently, considering four out of six top CO2 emitters mentioned above [i.e. China, India, the Russian Federation, and the EU(28)], and also the global level (i.e. the World), we illustrate the relationship between CO2 emissions and GDP per capita descriptively<sup>9</sup>, using both descriptive and nonparametric statistical techniques. Regarding the nonparametric techniques, we employ the local linear, local polynomial, and lowess nonparametric regressions models to better disentangle the pattern between CO2 pollution and economic growth. In doing so, we consider the standard specification of a general nonparametric model as follows:

$$y = \phi(x) + \varepsilon \quad (1)$$

We proxy environmental degradation by CO2 emissions per capita and economic growth by GDP per capita. The data are collected from the World Bank (2018) and the Janssens-Maenhout et al. (2017), for the period 1970-2016<sup>10</sup>. Next, equation (1) becomes:

$$CO2 = \phi(GDP) + \varepsilon \quad (2)$$

The CO2 is the endogenous variable, GDP is the predictor variable and  $\varepsilon \sim NID(0, \sigma^2)$  the error term.  $\phi(\cdot)$  denotes the unknown smooth continuous function, whose functional form is not specified, i.e. is estimated based on data<sup>11</sup>.

Column [A] from Figure 1 displays the evolution of CO2 emissions and GDP for each country. In contrast, column [B] and column [C] shows the scatter plot between indicators, and the curve fitting of nonparametric regressions<sup>12</sup>, respectively. First, we can observe that China, India, and the World exhibit a relatively smooth monotonically increasing relationship. At the same time,

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<sup>9</sup> We exclude Japan and the US from our analysis, considering that they belong to the group of developed countries. However, we keep the EU(28) and include the World as they also comprise the developing and transition countries.

<sup>10</sup> Due to data availability for the EU(28), the Russian Federation, and at the global level, the period covered is 1990-2016. Also, in the empirical analysis, we use the natural logarithm of the data.

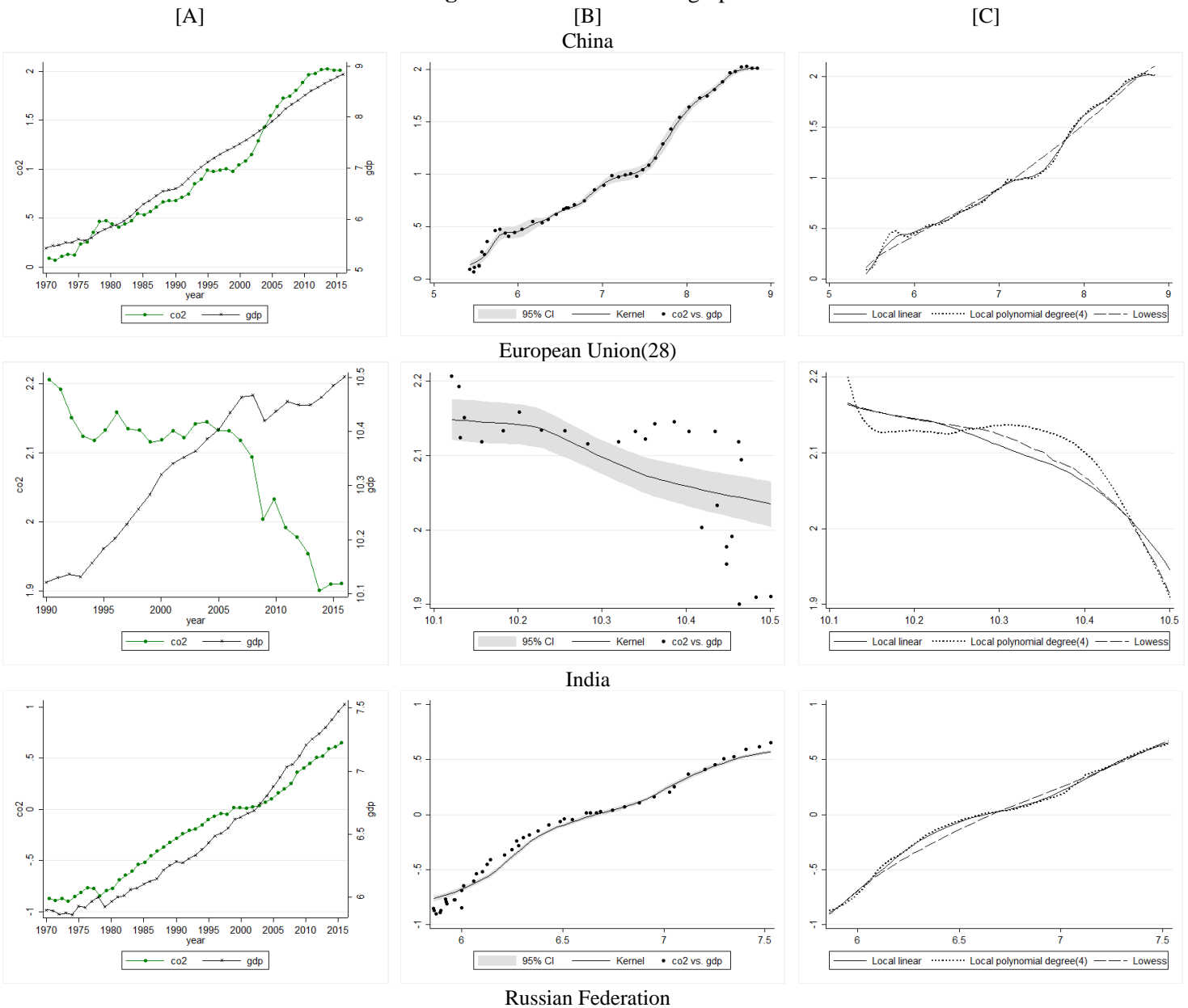
<sup>11</sup> For more information related to nonparametric regression models, see Cleveland (1979), Cleveland (1981), Robinson (1983), Cleveland and Devlin (1988), Cleveland and Loader (1996), Henderson and Parameter (2015), among others.

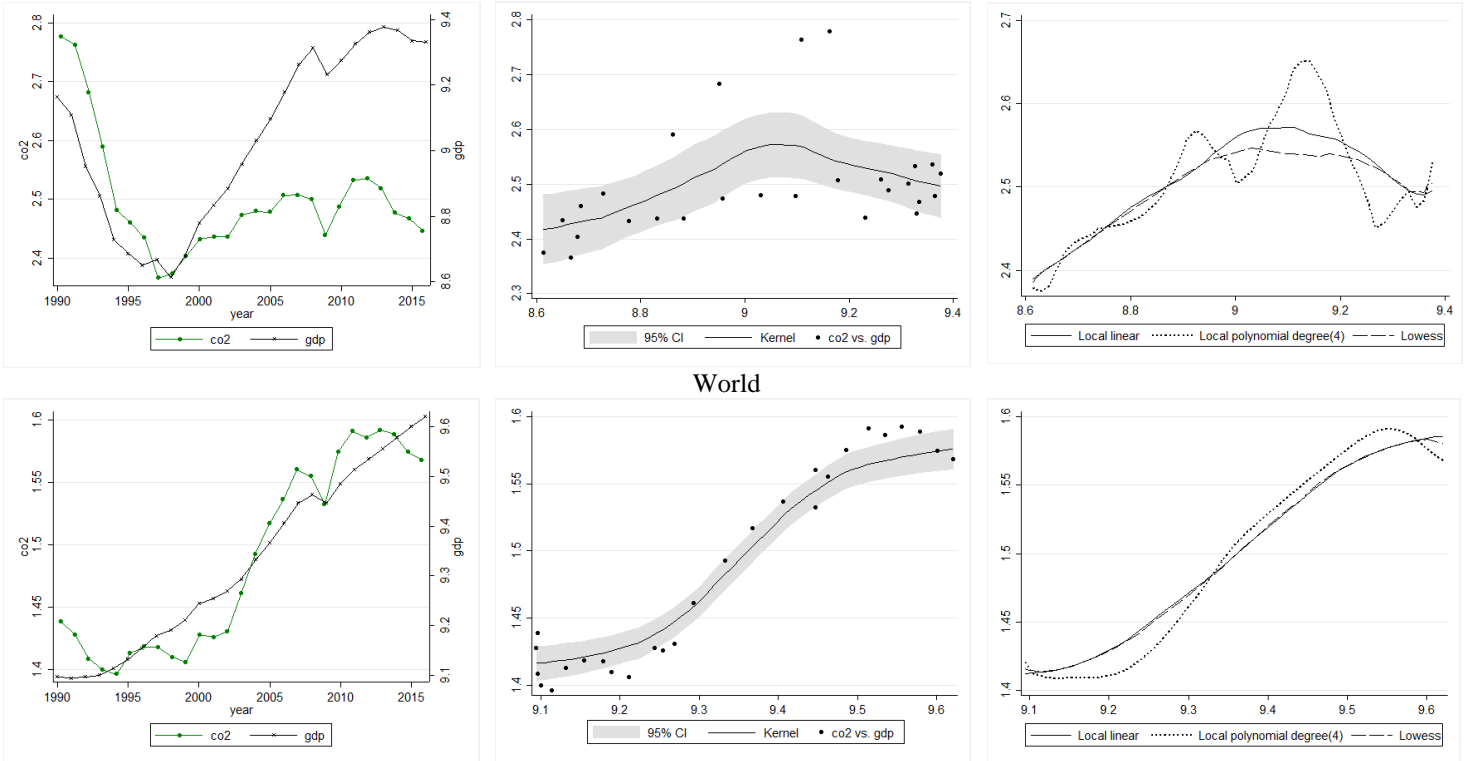
<sup>12</sup> We present the nonparametric regression models solely in a descriptive way, to better visualize and disentangle the pollution-growth nexus patterns. As such, we do not concern ourselves with variable nonstationary, cointegration, and other technical aspects related to time-series econometrics, these being beyond the aim of the present study. However, we note that some of those aspects are discussed during the paper theoretically.



in the EU(28), and the Russian Federation, the nonlinearities are more pronounced. Second, overall, the pollution decreases with economic development in the EU(28), and we note the opposite in the remaining cases. Third, judging at the descriptive level, the EKC hypothesis seems to hold only for the Russian Federation. Altogether, the straightforward descriptive analysis from Figure 1 emphasizes some important disparities related to the relationship between CO2 emissions and growth among countries considered. In the next section, we aim at presenting more in-depth empirical findings related to pollution-growth patterns of some recent studies that have tested the EKC hypothesis.

**Figure 1.** CO2-GDP nexus graphs





Notes: Column [A] shows the evolution of CO<sub>2</sub> emissions and GDP per capita during the period analyzed. In column [B], along with the scatterplot, we fitted a local constant kernel regression with 95% confidence bands. In column [C], we performed a local linear, local polynomial of degree(4) and lowess regression. For the kernel, local linear, and local polynomial, we specify the default Epanechnikov function and (0.1) bandwidth. The default bandwidth option is used for lowess regression.

#### IV. Empirical literature review on EKC hypothesis

Our survey attempts to bring together some of the papers that have stressed the relationship between pollution and growth through the EKC hypothesis for developing and transition states, and are published in the literature during the period from 2010 to 2019<sup>13</sup>. In this respect, first, we divide our empirical literature review into three parts, namely panel data analysis, time-series analysis, and the last part, which addresses some of the new perspectives on modeling environmental degradation and economic growth nexus. The first two parts are related to the time-domain approach<sup>14</sup>, while the last one lies both in time- and time-frequency-domain. Moreover, each of these parts corresponds to one standalone sub-section as below. Second, related to each paper, we provide information about the authors and the year of publication, sample, time-span, empirical methodology, endogenous variable, pollution-growth pattern, and the estimated income

<sup>13</sup> We note that the review of the literature is not exhaustive, as we include studies published between 2010 and 2019 in popular journals on the subject, which meet the needs of the present work.

<sup>14</sup> The studies that embody both types of analysis are included in the section in which we consider that the primary analysis harmonize.

turning point value.

#### *4.1. Panel data analysis*

Table 2 displays the studies that use panel data models to explore the EKC hypothesis. For a more homogeneous view, we split the items based on the specific technique approached, namely cointegration techniques and other panel data methods.

The first strand of studies uses larger groups of countries, which are further divided according to income level, and test the EKC hypothesis for the sub-samples of developing and/or transition countries (see Albuлесcu et al., 2019; Chen et al., 2019; Kim et al., 2019; Ridzuan, 2019; Alvarado et al., 2018; Luzzati et al., 2018; Omri, 2018; and Ulucak and Bilgili, 2018). The majority of these works use CO<sub>2</sub> emissions as the leading indicator of environmental pollution, except Ulucak and Bilgili (2018), who proxy environmental degradation with the ecological footprint, and Chen et al. (2019) and Ridzuan (2019) who use local pollutants. Moreover, two studies out of eight, namely Omri (2018) and Ulucak and Bilgili (2018), employ cointegration techniques, and both provide evidence in favor of the traditional EKC hypothesis. Likewise, the remaining works employ other panel data models, such as FE, RE, 2SLS, quantile regression models or semi-, and non-parametric models. Overall, the findings indicate a bell-shaped pattern between pollution and growth (with the notable exception of Luzzati et al., 2018, who find a monotonically increasing pattern for CO<sub>2</sub> emissions and a U-shaped pattern for total primary energy supply). Regarding the turning point, Chen et al. (2019), for the inverted U-shaped curve, estimate that its value in per capita terms equals 9112.90 US\$ (PM<sub>2.5</sub>), 8102.51 US\$ (PM<sub>10</sub>), and 9901.53 US\$ (SO<sub>2</sub>), while Luzzati et al. (2018), for the U-shaped curve, find that its value is 498 US\$ (total primary energy supply).

The second strand of studies investigates the EKC validity considering almost exclusively developing and transition economies samples. In this regard, Leblois et al. (2017) examine the deforestation rate EKC hypothesis for a group of 128 developing countries over the period 2002-2010. Based on the FE estimator, the results suggest the lack of a significant statistical link between environmental degradation and economic growth. In the same vein, Culas (2012) explores the relationship between the rate of deforestation and growth for 43 tropical developing nations, categorized by geographical region, namely, Latin America, Africa, and Asia. The findings reveal a bell-shaped pattern for Latin America and Africa, with a turning point computed at 6072 and

1483 US\$ per capita, respectively. For Asia, the relationship is found to be U-shaped, and the level of GDP for which the rate of deforestation switches its trend is about 2320 US\$ per capita. Also, Joshi and Beck (2018) point out that the relationship between CO<sub>2</sub> emissions and growth for 87 non-OECD countries is monotonically increasing. Hove and Tursoy (2019) and Özokcu and Özdemir (2017) also test the EKC hypothesis for 24 and 52 emerging countries, respectively. The former authors show that the pattern is inverted U-shaped (U-shaped) for nitrous oxide emissions (CO<sub>2</sub> emissions and fossil fuel consumption). In contrast, the latter authors unveil an N-shape pattern for CO<sub>2</sub> emissions.

Furthermore, to examine the pollution-growth pattern several researcher use specific group of countries, namely MENA or Middle East states (Arouri et al., 2012; Ozcan, 2013; Charfeddine and Mrabet, 2017), BRIC states (Pao and Tsai, 2010, 2011), African states (Osabuohien et al., 2014; Awad et al., 2019), ASEAN or Asian states (Hanif et al., 2019; Nasir et al., 2019), CEE states (Lazăr et al., 2019), SAARC states (Waqih et al., 2019), or newly industrialized states (Destek and Sarkodie, 2019). As such, Arouri et al. (2012) validate the CO<sub>2</sub> EKC hypothesis for 12 MENA states covering the period 1981-2005. The turning point of CO<sub>2</sub> emissions is found for a GDP level of 37,263 US\$ per capita. Charfeddine and Mrabet (2017) test the EKC hypothesis for ecological footprint using a sample of 15 MENA countries observed over the period 1995-2007. The empirical findings suggest a bell-shaped pattern for the whole sample and oil-exporting countries and a U-shaped pattern for non-oil-exporting countries. Likewise, the results provided by Ozcan (2013), based on the FMOLS estimator, unveil a U-shaped pattern between CO<sub>2</sub> emissions and growth, with an income threshold equals to 8.23 in logs. The study is conducted for 12 Middle East nations, span over the period from 1990 to 2008. Also, using cointegration techniques, Pao and Tsai (2010, 2011) confirm the presence of the bell-shaped pattern between CO<sub>2</sub> emissions and growth in BRIC countries. The computed income turning points for the convex curve are 5.638 and 5.393 in logs, respectively. Moreover, Awad et al. (2019) for 46 African states and Osabuohien et al. (2014) for 50 African states find evidence in favor of the EKC hypothesis, both for CO<sub>2</sub> emissions and air pollution measured as mean annual exposure, and CO<sub>2</sub> and PM<sub>10</sub> emissions, respectively. In the same vein, for 15 developing Asian states using the ARDL approach, Hanif et al. (2019), validate the CO<sub>2</sub> EKC hypothesis, while Nasir et al. (2019) for 5 ASEAN economies using FMOLS and DOLS estimators unveil a monotonically increasing pattern. Besides, the findings of Destek and Sarkodie (2019) for 11 newly industrialized countries,

and Waqih et al., (2019) for 4 SAARC countries, using panel cointegration techniques, reveal a bell-shaped pattern for ecological footprint and CO<sub>2</sub> emissions, respectively. Also, Lazăr et al. (2019) unveil a monotonically increasing pattern between economic growth and a series of pollution indicators, such as CO<sub>2</sub> emissions, SO<sub>2</sub> emissions, biocapacity, and ecological footprint. The authors employ a series of heterogeneous panel estimators, namely MG-FMOLS, MG, and AMG, for CEE states over the period 1996-2015. On this last point, it is worth noting that all these papers use panel cointegration techniques to investigate the pollution-growth nexus pattern.

The third strand of works uses panel data models to investigate the pattern between pollution and growth for Chinese provinces. In this regard, a group of studies shows that EKC is at work for Chinese provinces (Du et al., 2012; Chen and Chen, 2015; Hao et al., 2016; Li et al., 2016; Wang et al., 2016; Zhang et al., 2017; Chen et al., 2018; Hao et al., 2018b; Wenbo and Yan, 2018; Liu et al., 2019), while other studies reveal either an inverted N-shaped pattern (Liu et al., 2015; Kang et al., 2016; Li et al., 2019; Zhao et al., 2019) or a monotonically increasing pattern (Yang et al., 2015). More specifically, evidence in favor of EKC hypothesis is found for CO<sub>2</sub> emissions (Du et al., 2012; Chen and Chen, 2015; Li et al., 2016; Chen et al., 2018; Wenbo and Yan, 2018; Liu et al., 2019), CO<sub>2</sub> emission intensity (Wenbo and Yan, 2018), SO<sub>2</sub> emissions (Wang et al., 2016), coal consumption (Hao et al., 2016), wastewater and solid waste emissions (Li et al., 2016), COD and NH<sub>3</sub>-N emissions (Zhang et al., 2017), and soot and dust emissions (Chen et al., 2018). Moreover, the inverted N-shaped pattern occurs for CO<sub>2</sub> emissions (Liu et al., 2015; Kang et al., 2016), SO<sub>2</sub> emissions and solid waste (Zhao et al., 2019), and carbon intensity of human wellbeing (Li et al., 2019). Besides, Yang et al. (2015) find a monotonically increasing relationship for CO<sub>2</sub> emissions and industrial gas, while Hao et al. (2018b) a U-shaped pattern for the environmental quality index, which translates in a bell-shaped one, as the dependent variable is an inverse indicator of environmental degradation. With respect to the income turning points, the recent studies of Li et al. (2019) and Zhao et al. (2019) show that their estimated values based on the inverted N-shaped curve are 850 and 110,000 yuan per capita for carbon intensity of human wellbeing, and 4057 and 24,484 yuan per capita (4298 and 33,355 yuan per capita) for SO<sub>2</sub> emissions (solid waste), respectively. Moreover, for CO<sub>2</sub> emissions, Chen and Chen (2015) and Liu et al. (2019) find an income peak of the bell-shaped curve equals to 49,813.79 and 55,297.3 yuan per capita, respectively. Hao et al. (2016) show that the value of the income threshold of the coal consumption bell-shaped curve ranges between 18,456 to 23,585 yuan per capita (39,692 to

48,521 yuan per capita) for classical panel models (spatial panel models). Additionally, studies such as Du et al. (2012), Kang et al. (2016), Li et al. (2016), Hao et al. (2018b), and Li et al. (2019) find turning points that lie outside the income range values. However, the EKC patterns and the estimated turning points depend on the sample size (i.e. the number of provinces included), the period analyzed, and the proxy used for environmental degradation.

Other studies examine the EKC hypothesis either for the economic sectors of Iranian provinces (Dehghan Shabani and Shahnazi, 2019), metropolitan regions of Republic of Korea (Park and Lee, 2011), Indian cities (Sinha and Bhattacharya, 2017), or Chinese cities (Stern and Zha, 2016; Hao et al., 2018a). On the one hand, the results of Dehghan Shabani and Shahnazi (2019) based on the DOLS estimator illustrate that the EKC is at work for the period 2002-2013 for all economic sectors (i.e. agricultural, industrial, transportation, and services sector). However, the estimated turning points, namely 0.134 in logs (agricultural sector), 0.918 in logs (industrial sector), 0.880 in logs (transportation sector), and 0.555 in logs (services sector), are above the average GDP value for each sector. On the other hand, Sinha and Bhattacharya (2017) use a sample of 139 Indian cities and test the SO<sub>2</sub> EKC hypothesis for the period 2001-2013. Overall, the authors find a bell-shaped pattern for industrial and industrial high-income areas, while for industrial low-income areas, the relationship seems to be N-shaped. Also, for residential areas, the SO<sub>2</sub> growth nexus pattern does not exhibit nonlinearities. The SO<sub>2</sub> emissions peak varies from 18.87 to 1110.10 Rs. Lacs, for the electricity consumption model, and from 20.51 to 1564.36 Rs. Lacs, for the petroleum consumption model, according to income level sub-samples. Both the lowest values, i.e. 18.87 and 20.51, are situated outside the income range values. In the same vein, Stern and Zha (2016) investigate the EKC hypothesis for 50 Chinese cities over the period 2013-2014 using both the growth rates and traditional EKC models. Overall, according to both approaches, the pattern between pollution and growth seems to be U-shaped. Also, the computed turning point based on the traditional model and FE estimator is 453,454 RMB per capita for PM<sub>2.5</sub> (yet not statistically significant) and 87,493 RMB per capita for PM<sub>10</sub>. Also, Hao et al. (2018a) test the pollution-growth nexus pattern for 283 Chinese cities span over 2003-2010. The authors use three environmental degradation indicators, namely SO<sub>2</sub> emissions, industrial soot emissions, and industrial wastewater discharge, and apply the GMM technique. They show that the inverted U-shaped curve holds for soot emissions, while for SO<sub>2</sub> emissions, the pattern is U-shaped. Furthermore, using a dataset of 16 metropolitan regions from the Republic of Korea,

covering the period 1990-2005, Park and Lee (2011) show that relationship form between SO<sub>2</sub> emissions and growth is N-shaped (with the peak equals to 5700 US\$ and the trough equals to 28,000 US\$ per capita). Conversely, a U-shaped curve is at work for CO<sub>2</sub> emissions (with the peak that ranges from 26,400 US\$ to 30,000 US\$ per capita) and NO<sub>2</sub> emissions (with the peak equals to 27,600 US\$ per capita).

**Table 2.** Panel data literature survey

Author	Sample	Period	Methodology	Endogenous variable	Pollution-growth pattern	Turning point
<i>Cointegration analysis</i>						
Awad et al. (2019)	46 African countries	1990-2017	FMOLS, DOLS	CO <sub>2</sub> emissions, air pollution measured as mean annual exposure	Bell-shape	-
Dehghan Shabani and Shahnazi (2019)	28 provinces of Iran	2002-2013	DOLS	CO <sub>2</sub> emissions	Bell-shape	0.134* in logs (agricultural sector), 0.918* in logs (industrial sector), 0.880* in logs (transportation sector), 0.555* in logs (services sector)
Destek and Sarkodie (2019)	11 newly industrialized countries	1977-2013	AMG	Ecological footprint	Bell-shape	-
Hanif et al. (2019)	15 Asian developing countries	1990-2013	ARDL	CO <sub>2</sub> emissions	Bell-shape	-
Lazār et al. (2019)	11 CEE countries	1996-2015	MG-FMOLS, MG, AMG	CO <sub>2</sub> emissions, SO <sub>2</sub> emissions, biocapacity, ecological footprint	Monotonically increasing	-
Nasir et al. (2019)	5 ASEAN countries	1982-2014	FMOLS, DOLS	CO <sub>2</sub> emissions	Monotonically increasing	-
Waqih et al. (2019)	4 SAARC countries	1986-2014	ARDL, FMOLS	CO <sub>2</sub> emissions	Bell-shape	-
Omri (2018)	69 countries (high-income countries, upper-middle-income countries, lower-middle-income countries, low-income countries)	2001-2011	FMOLS	CO <sub>2</sub> emissions	Bell-shape (lower-middle-income countries, low-income countries)	-
Ulucak and Bilgili (2018)	45 countries (low-income countries, middle-income countries, high-income countries)	1961-2013	CUP-FM, CUP-BC	Ecological footprint	Bell-shape (low-income countries)	-
Charfeddine and Mrabet (2017)	15 MENA countries	1975-2007	FMOLS, DOLS	Ecological footprint	Bell-shape (panel, oil-exporting countries), U-shape	-

					(non-oil-exporting countries)	
Osabuohien et al. (2014)	50 African countries	1995-2010	DOLS	CO2 emissions, PM10 emissions	Bell-shape	-
Ozcan (2013)	12 Middle East countries	1990-2008	FMOLS	CO2 emissions	Ushape	8.23 in logs
Arouri et al. (2012)	12 MENA countries	1981-2005	CCE-MG	CO2 emissions	Bell-shape	37,263 US\$ per capita {constant 2005}
Pao and Tsai (2011)	BRIC countries	1980-2007, 1992-2007 (Russia)	Cointegration techniques	CO2 emissions	Bell-shape	5.638 in logs
Pao and Tsai (2010)	BRIC countries	1971-2005, 1990-2005 (Russia)	Cointegration techniques	CO2 emissions	Bell-shape	5.393 in logs
<i>Other panel data models</i>						
Albulescu et al. (2019)	14 Latin America countries (high-income countries, low-income countries)	1980-2010	FE, RE, FE panel quantiles regression	CO2 emissions	Bell-shape for the first quantiles (low-income countries)	-
Chen et al. (2019)	62 countries (35 more developed countries, 27 less developed countries)	1970-2012	FE, 2SLS	PM2.5 emissions, PM10 emissions, SO2 emissions	Bell-shape (27 less developed countries)	9112.90 US\$ per capita (PM2.5), 8102.51 US\$ per capita (PM10), 9901.53 US\$ per capita (SO2) {constant 2010}
Hove and Tursoy (2019)	24 emerging economies	2000-2017	GMM	CO2 emissions, fossil fuel energy consumption, nitrous oxide emissions	Bell-shape (nitrous oxide emissions), U-shape (CO2 emissions, fossil fuel consumption)	-
Kim et al. (2019)	131 countries (developing countries, advanced countries)	1960-2013	Panel data IV quantile regression	CO2 emissions	Bell-shape (developing countries)	-
Li et al. (2019)	30 provinces of China	1995-2016	Spatial panel models	Carbon intensity of human wellbeing	Inverted-N shape	850 yuan per capita and 110,000* yuan per capita {constant 2000}
Liu et al. (2019)	29 provinces of China	1996-2015	FE panel data partially linear additive model	CO2 emissions	Bell-shape	55,297.3 yuan per capita {deflated to the 1996 consumer price index}
Ridzuan (2019)	170/174 countries (high-income countries, low-income countries)	1991-2010	Driscoll and Kraay nonparametric variance-covariance estimator	SO2 emissions	Bell-shape (low-income countries)	-
Zhao et al. (2019)	30 provinces of China	1999-2017	Spatial regression models	SO2 emissions, solid waste, wastewater	Inverted-N shape (SO2 emissions, solid waste)	4057 and 24,484 yuan per capita (SO2), 4298



				discharge		and 33,355 yuan per capita (solid waste) {constant 2000}
Alvarado et al. (2018)	151 countries (high-income countries, middle-high-income countries, middle-low-income countries, low-income countries)	1980-2016	FE, RE	CO2 emissions	Bell-shape (middle-low-income countries)	-
Chen et al. (2018)	30 provinces of China	1998-2012	GMM	CO2 emissions, soot and dust emissions, wastewater discharge	Bell-shape (CO2 emissions, soot and dust emissions)	-
Hao et al. (2018a)	283 Chinese cities	2003-2010	GMM	SO2 emissions, industrial soot emissions, industrial wastewater discharged	Bell-shape (soot emissions), U-shape (SO2 emissions)	-
Hao et al. (2018b)	30 provinces of China	2006-2015	Nonspatial models (pooled OLS, spatial FE, time period effects, spatial and time-period effects), spatial Durbin model	Environmental quality index	N-shape (which translates in a bell-shape curve as the dependent variable is an indirect indicator of environmental degradation)	9500 RMB per capita 420,000* RMB per capita {constant 2005}
Joshi and Beck (2018)	87 non-OECD	1995-2010	GMM	CO2 emissions	Monotonically increasing	-
Luzzati et al. (2018)	115 countries (low-income countries, middle-income countries, high-income countries)	1971-2015	Semi-parametric model, FGLS	CO2 emissions, total primary energy supply	Monotonically increasing (low-income countries; CO2 emissions), U-shape (low-income countries; total primary energy supply)	498 US\$ per capita (total primary energy supply) {constant 2010}
Wenbo and Yan (2018)	30 provinces of China	2004-2015	GMM	CO2 emissions, CO2 emissions intensity	Bell-shape	-
Leblois et al. (2017)	128 developing countries	2002-2010	FE	Deforestation rate	No statistical link	-
Özokcu and Özdemir (2017)	52 emerging countries	1980-2010	FE, Driscoll-Kraay Standard Errors	CO2 emissions	N-shape	-
Sinha and Bhattacharya (2017)	139 Indian cities	2001-2013	FE, RE	SO2 emissions	Electricity model: bell-shape (industrial, industrial high-income areas), N-shape (industrial low-income areas), linear (residential,	Electricity model: 452.24 Rs. Lacs (industrial), 1110.10 Rs. Lacs (industrial high-income), 18.87* Rs. Lacs and 5604.37 Rs.

					residential low-income areas) Petroleum model: bell-shape (industrial, industrial high-income areas), N-shape (industrial low-income areas), linear (residential areas), monotonically increasing (residential low-income areas), monotonically decreasing (residential medium-income areas)	Lacs (industrial low-income) Petroleum model: 287.52 Rs. Lacs (industrial), 1564.36 Rs. Lacs (industrial high-income), 20.51* Rs. Lacs and 5799.40 Rs. Lacs (industrial low-income)
Zhang et al. (2017)	27 provinces of China	(a) 1990-2014, (b) 2001-2014	FE, B-spline regression (parametric and semi-parametric models), cointegration analysis	(a) COD emissions (b) NH3-N emissions	Bell-shape	-
Kang et al. (2016)	30 provinces of China	1997-2012	Nonspatial model (pooled OLS, spatial FE, time-period FE, spatial and time-period FE), spatial Durbin model (spatial FE, time-period FE, spatial and time-period FE, spatial RE and time	CO2 emissions	Inverted-N shape	1545.03* and 57,308.26 RMB per capita (nonspatial two-way FE models), 1480.30* and 82,677.27* RMB per capita (SDM FE models) {constant 1997}
Li et al. (2016)	28 provinces of China	1996-2012	GMM, ARDL (PMG, MG, DFE)	CO2 emissions, industrial wastewater emissions, industrial waste solid emissions	Bell-shape	10,403.96* US\$ per capita (CO2 emissions), 1063.88 US\$ per capita (wastewater emissions), 23,076.99* US\$ per capita (waste solid emissions) {constant 2012}
Hao et al. (2016)	29 Chinese provinces	1995-2012	Nonspatial panel models (pooled OLS, individual FE, time FE, individual and time FE), spatial Durbin models (individual and time FE, individual and time FE bias-	Coal consumption	Bell-shape	18,456 to 23,585 yuan per capita (panel models), 39,692 to 48,521 yuan per capita (spatial panel models) {constant 1978}

			corrected, random individual effects, fixed time effects)			
Stern and Zha (2016)	50 Chinese cities	2013-2014	FE	PM2.5 emissions, PM10 emissions	U-shape	453,454* RMB per capita (PM2.5; not statistically significant), 87,493 RMB per capita (PM10)
Wang et al. (2016)	Chinese provinces	1990-2012	Parametric and semi-parametric FE	SO2 emissions	Bell-shape	-
Liu et al. (2015)	31 provinces of China	1997-2010	OLS FE	CO2 emissions	Inverted-N shape	127.41 and 10,201.29 yuan per capita {constant 1997}
Chen and Chen (2015)	31 Chinese provinces	1985-2010	Nonparametric and parametric regression	CO2 emissions	Bell-shape	49,813.79 yuan per capita (10.81 in logs)
Yang et al. (2015)	29 provinces of China	1995-2010	Extreme Bound Analysis (General Sensitivity Test), bootstrapping method	CO2 emission, SO2 emission, industrial dust, industrial waste gas, industrial smoke, industrial SO2 emissions, industrial wastewater	Monotonically increasing (CO2 emissions, industrial gas)	-
Culas (2012)	43 tropical developing nations (Latin America, Africa, Asia)	1971-1994	FE, RE	Rate of deforestation	Bell-shape (Latin America, Africa), U-shape (Asia)	6072 US\$ per capita (Africa), 1483 US\$ per capita (Latin America), 2320 US\$ per capita (Asia) {constant 1995}
Du et al. (2012)	29 provinces of China	1995-2009	FE, Biased-corrected LSDVC, GMM	CO2 emissions	Bell-shape	1.214e+15*/1.372e+14*/1.563e+14* yuan per capita {constant 1995}
Park and Lee (2011)	16 metropolitan regions in Republic of Korea	1990-2005	FE, RE, RCM	SO2 emissions, CO emissions, NO2 emissions	N-shape (SO2), U-shape (CO, NO2)	5700 and 28,000 US\$ per capita (SO2), 26,400 to 30,000* US\$ per capita (CO), 27,600 US\$ per capita (NO2) {constant 2000}

Notes: ARDL-Autoregressive Distributed Lag; ASEAN-Association of Southeast Asian Nations; CEE-Central and Eastern Europe; CCE-MG-Common Correlated Effects Mean Group; COD-Chemical Oxygen Demand; CO2-Carbon Dioxide; CUP-BC-Continuously Updated Bias Corrected; CUP-FM-Continuously Updated Fully Modified; DFE-Dynamic Fixed Effects; DOLS-Dynamic OLS; FMOLS-Fully Modified OLS; FE-Fixed Effects; GMM-Generalized Method of Moments; MG-Mean Group; NH3-N-Discharge and Ammonia Nitrogen; NO2-Nitrogen dioxide; PMG-Pooled Mean Group; PSTR-Panel Smooth Transition Regression; RE-Random Effects; RMC-Random Coefficient Model; SAARC-South Asian Association for Regional Cooperation; SO2-Sulfur Dioxide; VAR-Vector Autoregression; VECM-Vector Error Correction Model; 2SLS-Two-Stage Least Squares. The "-" indicates that the turning point is not computed, while the "\*" indicates that the estimated turning point is out of sample values. When both long- and short-run analysis is present, we report the pollution-growth nexus pattern and turning point associated with the long-run results. The methodology column gives information about the technique used in investigating the pollution-growth pattern, even if the respective study comprises other statistical and econometric techniques. All the information contained in the table represents our interpretation of the results in the analyzed studies.

#### 4.2. Time-series analysis

The country-specific works that tackle the relationship between growth and environmental pollution through the EKC hypothesis are listed in Table 3. At first glance, we can observe that most researchers use the ARDL bounds test approach technique to investigate the validity of the EKC hypothesis. Also, the FMOLS and DOLS techniques appear frequently as econometric tools in investigating pollution-growth pattern.

First, focusing on China, several contributions (Jalil and Feridun, 2011; Jayanthakumaran et al., 2012; Alam et al., 2016; Adebola Solarin et al., 2017; Wolde-Rufael and Idowu, 2017; Riti et al., 2017; Dong et al., 2018; and Chen et al., 2019) find empirical evidence in favor of traditional CO<sub>2</sub> EKC hypothesis. Also, while Riti et al. (2017) estimate the peak value of the bell-shape curve within the income range values, the findings of Jalil and Feridun (2011) and Dong et al. (2018) indicate that the turning point lies outside the sample values. However, the authors cover different periods, and in particular, the three studies which compute the bell-shaped curve maxima, span the period 1978-2006 (Jalil and Feridun, 2011), 1970-2015 (Riti et al., 2017), and 1993-2016 (Dong et al., 2018). Conversely, Onafowora and Owoye (2014) conclude that the pattern between CO<sub>2</sub> emission and growth is N-shaped, while the associated income peak is equal to 17.050 in logs, and outside of sample values. Moreover, based on the FMOLS estimator Yao et al. (2019) reveal a monotonically increasing relationship for CO<sub>2</sub> emissions. Besides, using environmental quality index (i.e. an inverse indicator of environmental pollution), the results provided by Wang et al. (2015) validate the EKC hypothesis for Gansu province in China. More specifically, the authors employ a Bayesian VAR model, and find a U-shaped pattern between the indicators for the period 1980-2012, with the estimated income threshold value of 2273 RMB per capita.

Second, for Malaysia, the empirical findings seems to cover a broad spectrum of patterns, such as the traditional bell-shaped (Saboori et al., 2012; Saboori and Sulaiman, 2013b; Lau et al., 2014; Ali et al., 2017; Azam et al., 2018), the U-shaped (Begum et al., 2015; Chandran and Tang, 2013), the inverted N-shaped (Bekhet and Othman, 2018), the monotonically increasing relationship (Azlina et al., 2014), or no statistical link (Saboori and Sulaiman, 2013a). Furthermore, Saboori et al. (2012) and Saboori and Sulaiman (2013b) unveil that the computed GDP maxima of the bell-shaped curve for the period 1980-2009 is 4700 US\$ per capita, and depending on the model 5378/5825/6003/8267 US\$ per capita, respectively. However, it is worth noting that the estimated peak value of Saboori and Sulaiman (2013b) lies outside the GDP sample

values. As well, considering the inverted N-shaped curve, Bekhet and Othman (2018) reveal that the pollution switches its trend for a GDP value of 170.9 RM billion (trough) and 2841.9 RM billion (peak). However, the income peak lies outside the sample range values.

Third, with respect to CO<sub>2</sub> EKC for Indonesia, two studies show that the bell-shaped pattern is supported by data (Alam et al., 2016; Sugiawan and Managi, 2016), while other three studies reveal mixed results, namely a monotonically increasing relationship (Yao et al., 2019; Chandran and Tang, 2013) or a U-shaped pattern (Saboori and Sulaiman, 2013a). Concerning the income threshold, Sugiawan and Managi (2016) estimate an out of sample turning point of 7729 US\$ per capita. Besides, Chandran and Tang (2013), along with Malaysia and Indonesia, examine the EKC hypothesis for Thailand, Singapore, and the Philippines, for the period 1971-2011. Overall, the empirical findings reject a long-run relationship between variables for the Philippines and Singapore, while for Thailand, the pattern seems to be convex, invalidating the EKC hypothesis. More recently, the empirical analysis of Azam et al. (2018) leads to the same conclusions, namely the presence of the U-shaped pattern for Thailand, and no statistically significant results for Singapore. Opposite, using DOLS estimator, Katircioğlu (2014) show that the EKC is valid for Singapore, for the period 1971-2010. Also, using the same sample of countries as Chandran and Tang (2013) to test the CO<sub>2</sub> EKC hypothesis, Saboori and Sulaiman (2013a) reveal that the inverted U-shaped pattern holds only for Singapore and Thailand. The income peak value is 8.65 in logs (Singapore), and 7.47 in logs (Thailand).

Fourth, the strand of papers that target the CO<sub>2</sub> EKC hypothesis for India show that in most cases the bell-shaped pattern holds (Jayanthakumaran et al., 2012; Tiwari et al., 2013; Kanjilal and Ghosh, 2013; Boutabba, 2014; Shahbaz et al., 2015; Wolde-Rufael and Idowu, 2017; Adebola Solarin et al., 2017; Sinha and Shahbaz, 2018; Yao et al., 2019), with the notable exception of Alam et al. (2016), who find that CO<sub>2</sub> pollution increases along with economic growth. With regard to the turning point, authors such as Tiwari et al. (2013) and Boutabba (2014) show that its estimated value is 28,131 Indian rupees per capita for the period 1996-2011, and 19,380 Indian rupees per capita for the period 1971-2008, respectively. Also, Yao et al. (2019) find that the threshold arises for an income value of 6.61 in logs, while Sinha and Shahbaz (2018) identify an out of sample turning point which corresponds to a value of 2937.77 US\$ per capita.

Fifth, the group of scholars that focus on Tunisia, unveil both a nonlinear bell-shaped relationship between CO<sub>2</sub> pollution and growth (Shahbaz et al., 2014; Farhani et al., 2014) and a

U-shaped pattern (Ben Jebli and Ben Youssef, 2015). Also, for the period 1961-2004, the results of Fodha and Zaghoud (2010) reveal an inverted U-shaped pattern for SO<sub>2</sub> (with an associated GDP turning point value of 1200 US\$ per capita), and a monotonically increasing one for CO<sub>2</sub>.

In the case of Pakistan, Nasir and Ur Rehman (2011) and Danish et al. (2017) provide evidence that supports the EKC hypothesis for CO<sub>2</sub> emissions, while according to Hussain et al. (2012) the pattern seems to be monotonically increasing. Moreover, according to Nasir and Ur Rehman's (2011) findings, the GDP threshold of the concave function is equal to 625 US\$ per capita. As well, the studies of Charfeddine (2017) and Mrabet and Alsamara (2017) also provide contradictory findings for Qatar. Using a Markov switching equilibrium correction model for the period 1970-2015, Charfeddine (2017) validates the EKC hypothesis for CO<sub>2</sub> emissions and carbon ecological footprint but fails to find evidence in favor of ecological footprint EKC (i.e. the results illustrate a U-shaped pattern). Conversely, Mrabet and Alsamara (2017), employing the ARDL bounds test approach, show that the relationship between CO<sub>2</sub> and growth is U-shaped, whereas, for ecological footprint, the traditional bell-shaped curve is at work.

The studies which examine the pollution-growth pattern for Turkey reveal, depending on pollution indicator, either a bell-shaped pattern (Bölük and Mert., 2015; Pata, 2018; Zambrano-Monserrate et al., 2018a; Huag and Ucal, 2019), an U-shaped pattern (Huag and Ucal, 2019) or no statistical link (Huag and Ucal, 2019; Yao et al., 2019). Besides, concerning the income turning point, Bölük and Mert (2015) and Pata (2018) reveal that its estimated value lies outside the income range, and equals 9920 US\$ and 14,360 US\$ per capita, respectively. Conversely, Zambrano-Monserrate et al. (2018a) and Huag and Ucal (2019) find a within-sample turning point value equals to 9031.37 US\$ and 7963.31 US\$ per capita (6385.59 US\$) for CO<sub>2</sub> emissions (CO<sub>2</sub> intensity), respectively.

Finally, several contributors that investigate the EKC hypothesis for other developing and transition economies unveil mixed results: (i) a monotonically increasing pattern [Al-Mulali et al. (2015) for Vietnam; Alshehry and Belloumi (2017) for Saudi Arabia; Zambrano-Monserrate et al. (2018) for Peru; Yao et al. (2019) for Russia]; (ii) a monotonically decreasing pattern [Pao et al. (2011) for Russia]; (iii) a U-shaped pattern [Ozturk and Al-Mulali (2015) for Cambodia; Halicioglu and Ketenci (2016) for Azerbaijan, Lithuania, Moldavia, Russia, and Tajikistan]; (iv) an inverted U-shaped pattern [Baek and Kim (2013) for Korea; Shahbaz et al. (2013) for Romania; Bouznit and Pablo-Romero (2016) for Algeria; Alam et al. (2016) for Brazil; Halicioglu and

Ketenci (2016) for Armenia, Belarus, Estonia, Kyrgyzstan, Turkmenistan, and Uzbekistan; Ahmad et al. (2017) for Croatia; Pata (2018); Yao et al. (2019) for Brazil, South Africa, and South Korea]; (v) an N-shaped pattern [Onafowora and Owoye (2014) for Brazil, Egypt, Mexico, Nigeria, and South Africa]; (vi) an inverted N-shaped pattern [Onafowora and Owoye (2014) for South Korea]; (vii) and also no statistical link [Halicioglu and Ketenci (2016) for Georgia, Kazakhstan, Latvia, and Ukraine]. Likewise, Narayan and Narayan (2010), using the cointegration approach for a sample of 43 developing countries over the period 1980-2004, conclude that only in about 35% of the sample, the downward-bending curve is at work.

Furthermore, the authors who compute the associated income turning point of the specific function reveal the following results. On the one hand, Onafowora and Owoye (2014) show that the peak (i.e. 22.083 in logs) of the N-shaped curve for Brazil lies outside the sample range, while Yao et al. (2019) unveil that the peak (i.e. 10.57 in logs) of the bell-shaped curve lies within the income sample values. On the other hand, the researchers that estimate the income peak value for South Africa reveal a similar behavior. As such, according to Onafowora and Owoye (2014), the estimated threshold (i.e. 22.963 in logs) value lies outside the sample range, while Yao et al. (2019) find the opposite (the estimated threshold equals 8.75 in logs). For Korea, Baek and Kim (2013) and Yao et al. (2019) reveal that the turning point of the bell-shaped curve lies well within the income sample values. Also, the studies which estimate the value of the income threshold for other states find values outside the sample range [Onafowora and Owoye (2014) for Egypt, Mexico, and Nigeria; Bouznit and Pablo-Romero (2016) for Algeria].

**Table 3.** Time-series literature survey

Author	Sample	Year	Methodology	Endogenous variable	Pollution-growth pattern	Turning point
Chen et al. (2019)	China	1980-2014	ARDL bounds test	CO2 emissions	Bell-shape	-
Huag and Ucal (2019)	Turkey	1974-2014	Linear and nonlinear ARDL bounds test approach	CO2 emissions, CO2 intensity, CO2 emissions from electricity and heat production, CO2 from manufacturing and construction, CO2 emissions from residential buildings, and commercial and public services, CO2 from transport	Bell-shape (CO2 emissions, CO2 intensity, CO2 from manufacturing and construction, CO2 emissions from residential buildings, and commercial and public services), U-shape (CO2 emissions from electricity and heat production), no statistical link (CO2 from transport)	7963.31 US\$ per capita (CO2 emissions), 6385.59 US\$ per capita (CO2 intensity) {constant 2010}

Yao et al. (2019)	17 major developing and developed countries	1990-2014	FMOLS, DOLS	CO2 emissions	Bell-shape (Brazil, India, South Africa, South Korea <sup>†</sup> ), monotonically increasing (China, Indonesia, Russia), no statistical link (Turkey)	10.57 in logs (Brazil), 6.61 in logs (India), 8.75 in logs (South Africa), 9.74 in logs (South Korea)
Azam et al. (2018)	Malaysia, Singapore, Thailand	1990-2014	FMOLS	CO2 emissions	Bell-shape (Malaysia), U-shape (Thailand), no statistical link (Singapore)	-
Bekhet and Othman (2018)	Malaysia	1971-2015	ARDL bounds test, FMOLS, DOLS	CO2 emissions	Inverted N-shape	170.9 RM billion and 2841.9* RM billion {constant 2010}
Dong et al. (2018)	China	1993-2016	ARDL bounds test, FMOLS, DOLS, CCR	CO2 emissions	Bell-shape	96,680.47* yuan per capita {constant 1990}
Pata (2018)	Turkey	1971-2014	ARDL bounds test	CO2 emissions	Bell-shape	14,360* US\$ per capita {constant 2010}
Sinha and Shahbaz (2018)	India	1971-2015	ARDL bounds test	CO2 emissions	Bell-shape	2937.77* US\$ per capita
Zambrano-Monserrate et al. (2018a)	France, Germany, Greece, Portugal, Turkey	1974-2013	ARDL bounds test	Deforestation (arable land)	Bell-shape (Turkey)	9,031.37 US\$ per capita {constant 2010}
Zambrano-Monserrate et al. (2018b)	Peru	1980-2011	ARDL bounds test	CO2 emissions	Monotonically increasing	-
Ali et al. (2017)	Malaysia	1971-2012	ARDL bounds test, DOLS	CO2 emissions	Bell-shape	-
Alshehry and Belloumi (2017)	Saudi Arabia	1971-2011	ARDL bounds test	Transport CO2 emissions	Monotonically increasing	-
Charfeddine (2017)	Qatar	1970-2015	Markov switching equilibrium correction model	CO2 emissions, carbon ecological footprint, ecological footprint	Bell-shape (CO2 emissions, carbon ecological footprint), U-shape (ecological footprint)	-
Danish et al. (2017)	Pakistan	1970-2012	ARDL bounds test, FMOLS, DOLS, CCR	CO2 emissions	Bell-shape	-
Mrabet and Alsamara (2017)	Qatar	1980-2011	ARDL bounds test	CO2 emissions, ecological footprint	Bell-shape (ecological footprint), U-shape (CO2)	-
Riti et al. (2017)	China	1970-2015	ARDL bounds test, ARDL, FMOLS, DOLS	CO2 emissions	Bell-shape	744,665* billion US\$ per capita {constant 2010}
Adebola Solarin et al. (2017)	China, India	1965-2013	ARDL bounds test	CO2 emissions	Bell-shape	-
Wolde-Rufael and Idowu (2017)	China, India	1974-2010 (China), 1971-2010 (India)	ARDL bounds test, FMOLS, DOLS	CO2 emissions	Bell-shape	-



Ahmad et al. (2017)	Croatia	1992Q1-2011Q1	ARDL bounds test, FMOLS, DOLS	CO2 emissions	Bell-shape	-
Alam et al. (2016)	Brazil, China, India, Indonesia	1970-2012	ARDL bounds test	CO2 emissions	Bell-shape (China, Brazil, Indonesia), monotonically increasing (India)	-
Bouznit and Pablo-Romero (2016)	Algeria	1970-2010	ARDL bounds test	CO2 emissions	Bell-shape	12.2*/10* in logs
Halicioglu and Ketenci (2016)	15 transition economies	1991-2013	ARDL bounds test, GMM	CO2 emissions	Bell-shape (Armenia, Belarus, Estonia, Kyrgyzstan, Turkmenistan, Uzbekistan), U-shape (Azerbaijan, Lithuania, Moldavia, Russia, Tajikistan), no statistical link (Georgia, Kazakhstan, Latvia, Ukraine)	-
Sugiawan and Managi (2016)	Indonesia	1971-2010	ARDL bounds test	CO2 emissions	Bell-shape	7729* US\$ per capita {constant 2005}
Al-Mulali et al. (2015)	Vietnam	1981-2011	ARDL bounds test	CO2 emissions	Monotonically increasing	-
Begum et al. (2015)	Malaysia	1970-2009	ARDL bounds test, DOLS, Sasabuchi-Lind-Mehlum U tests	CO2 emissions	U-shape	-
Bölük and Mert (2015)	Turkey	1961-2010	ARDL bounds test	CO2 emissions	Bell-shape	9920* US\$ per capita {constant 2005}
Ben Jebli and Ben Yousseff (2015)	Tunisia	1980-2009	ARDL bounds test	CO2 emissions	U-shape	-
Ozturk and Al-Mulali (2015)	Cambodia	1996-2012	GMM, 2SLS	CO2 emissions	U-shape	-
Shahbaz et al. (2015)	India	1970-2012	ARDL bounds test	CO2 emissions	Bell-shape	-
Wang et al. (2015)	Gansu province (China)	1980-2012	Bayesian VAR models	Environmental quality index	U-shape for Bayesian VAR models with Minnesota prior	2273 RMB per capita {constant 1980}
Azlina et al. (2014)	Malaysia	1975-2011	Johansen cointegration	CO2 emissions	Monotonically increasing	-
Boutabba (2014)	India	1971-2008	ARDL bounds test	CO2 emissions	Bell-shape	19,380 Indian rupees per capita
Farhani et al. (2014)	Tunisia	1971-2008	ARDL bounds test	CO2 emissions	Bell-shape	-
Katircioğlu (2014)	Singapore	1971-2010	DOLS	CO2 emissions	Bell-shape	-
Lau et al. (2014)	Malaysia	1970-2008	ARDL bounds test	CO2 emissions	Bell-shape	-
Onafowora and Owoye (2014)	Brazil, China, Egypt, Mexico, Nigeria, South	1970-2010	ARDL bounds test	CO2 emissions	N-shape (Brazil, China, Egypt, Mexico, Nigeria), inverted N-shape (South Korea),	22.083* in logs (Brazil), 17.050* in logs (China), 16.585* in logs (Egypt), 21.344*

	Africa, South Korea					in logs (Mexico), 32.855* in logs (Nigeria), 22.963* in logs (South Africa), 8.071 and 8.746 in logs (South Korea)
Shahbaz et al. (2014)	Tunisia	1971-2010	ARDL bounds test	CO2 emissions	Bell-shape	-
Baek and Kim (2013)	Korea	1978-2007	ARDL bounds test	CO2 emissions	Bell-shape	10,119/11,711 US\$ per capita, {constant 2010}
Chandran and Tang (2013)	Malaysia, Philippines, Thailand, Singapore, Indonesia	1971-2011	Johansen cointegration	CO2 emissions	U-shape (Malaysia, Thailand), monotonically increasing (Indonesia)	-
Kanjilal and Ghosh (2013)	India	1971-2008	Threshold cointegration	CO2 emissions	Bell-shape	-
Saboori and Sulaiman (2013a)	Indonesia, Malaysia, Philippines, Singapore, Thailand	1971-2009	ARDL bounds test	CO2 emissions	Bell-shape (Singapore, Thailand), U-shape (Indonesia, Philippines), no statistical link (Malaysia)	8.65 in logs (Singapore), 7.47 in logs (Thailand)
Saboori and Sulaiman (2013b)	Malaysia	1980-2009	ARDL bounds test	CO2 emissions	Bell-shape	5378*/6003*/8267*/5825* US\$ per capita {constant 2000}
Shahbaz et al. (2013)	Romania	1980-2010	ARDL bounds test	Energy emissions	Bell-shape	-
Tiwari et al. (2013)	India	1966-2011	ARDL bounds test	CO2 emissions	Bell-shape	28,131 Indian rupees (531 US\$) per capita
Hussain et al. (2012)	Pakistan	1971-2006	Johansen cointegration	CO2 emissions	Monotonically increasing	-
Jayanthakumaran et al. (2012)	China, India	1971-2007	ARDL bounds test	CO2 emissions	Bell-shape	-
Saboori et al. (2012)	Malaysia	1980-2009	ARDL bounds test	CO2 emissions	Bell-shape	4700 US\$ per capita {constant 2000}
Jalil and Feridun (2011)	China	(a) 1953-2006, (b) 1978-2006	ARDL bounds test	CO2 emissions	Bell-shape [(a), (b)]	(b) 11,071* to 13,421* RMB per capita {constant 2000}
Nasir and Ur Rehman (2011)	Pakistan	1972-2008	Johansen cointegration	CO2 emissions	Bell-shape	625 US\$ per capita {constant 2000}
Pao et al. (2011)	Russia	1990-2007	Johansen cointegration	CO2 emissions	Monotonically decreasing	-
Fodha and Zaghoud (2010)	Tunisia	1961-2004	VAR	SO2 emissions, CO2 emissions	Bell-shape (SO2), monotonically increasing (CO2)	1200 US\$ per capita (3700 PPP US\$ per capita) {constant 2000}

Narayan and Narayan (2010)	43 developing states	1980-2004	Cointegration analysis	CO2 emissions	Bell-shape (Jordan, Iraq, Kuwait, Yemen, Qatar, the UAE, Argentina, Mexico, Venezuela, Algeria, Kenya, Nigeria, Congo, Ghana, South Africa)	-
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Notes: ARDL-Autoregressive Distributed Lag; CCR-Canonical Cointegrating Regression; CO2-Carbon Dioxide; DOLS-Dynamic OLS; FMOLS-Fully Modified OLS; FE-Fixed Effects; GMM-Generalized Method of Moments; SO2-Sulfur Dioxide; VAR-Vector Autoregression; VECM-Vector Error Correction Model; 2SLS-Two-Stage Least Squares. The "-" indicates that the turning point is not computed, while the "\*" indicates that the estimated turning point is out of sample values. † Although South Korea was included in the developed country group, we report the associated EKC results as, in the present review, we treat it as an emerging market economy. When both long- and short-run analysis is present, we report the pollution-growth pattern and turning point associated with the long-run results. The methodology column gives information about the technique used in investigating the pollution-growth nexus pattern, even if the respective study comprises other statistical and econometric techniques. All the information contained in the table represents our interpretation of the results in the analyzed studies.

#### 4.3. *New perspectives on modelling environmental degradation and economic growth nexus*

A large majority of the empirical studies mentioned above apply classical econometric tools to check the validity of the EKC hypothesis. However, some novel techniques, such as wavelet analysis, has recently emerged in the related literature and has gained the attention of researchers. Compared with the classical econometric techniques that are part of the time-domain and the techniques associated with the frequency-domain (e.g. the Fourier approach), the wavelet analysis is much more flexible, in the sense that covers both the time- and frequency-domain (Schleicher, 2002). Thus, this type of analysis may provide a broader perspective on data behavior by allowing to investigate different time-horizons (e.g. short-, medium-, and long-term), and highlighting the potential nonlinearities, direction of causality, and lead-lag nexus (cyclical and counter-cyclical course) between variables at distinct frequencies and time-periods (Mutascu et al., 2016).

The empirical literature regarding wavelet analysis is relatively new and limited, with almost all studies focusing on modeling the environmental degradation-economic growth nexus for developed countries (see e.g. Mutascu et al., 2016, Fosten, 2019, Raza et al., 2019, among others). Concerning developing and transition countries, authors such as Jammazi and Aloui (2015) and Kalmaz and Kirikkaleli (2019) employ wavelet techniques to examine the relationship between environmental degradation and economic growth. Nevertheless, the EKC hypothesis is explicitly tested only in the study of Jammazi and Aloui (2015). The authors use a sample of six oil-exporting countries from the Gulf Cooperation Council (Saudi Arabia, Bahrain, Oman, United Arab Emirates, Qatar, and Kuwait), and based on wavelet windowed cross-correlation results, they show that the EKC hypothesis is valid for the period 1980-2012. More recently, Kalmaz and Kirikkaleli (2019) investigate the relationship between CO2 emissions and GDP, among other

variables, for Turkey. According to wavelet coherence analysis, overall, the findings suggest a positive correlation between CO<sub>2</sub> and GDP over the period 1960-2015.

Although wavelet analysis is recently adopted as a statistical tool in economics, it may represent a promising approach through which one can provide straightforward and valuable insights, and policy recommendations for different economic hypotheses such as EKC. Moreover, taking stock of the complexity of the phenomena and its interconnectedness that govern the field of energy and environmental economics, this type of approach that moves away from time-domain may add valuable information when used in empirical analysis, both solely or along with other techniques.

## **V. Conclusions and policy implications**

The quality of the environment plays a vital role in nations' welfare and remains a very debatable subject both at the international and national levels. Additionally, no single formula has yet been found to fit all economic contexts in terms of mitigating pollution and its adverse effects. Starting for the premise of sustainable development, the goal of this paper was to provide both a theoretical review of the key aspects of EKC and an updated empirical review of the pollution-growth nexus literature that focuses on the EKC hypothesis testing in developing and transition states.

Consequently, our updated survey may provide valuable information and, to some extent, positive prospects on EKC estimation, since the reviewed works angle towards a consensus both in terms of empirical strategy and the EKC validity. On the one hand, strengthening the EKC character, most of the studies unveiled a long-term relationship between environmental pollution and economic growth. In this fashion, the findings of numerous works emphasized a cointegration relationship between variables. Thus, concerning the related techniques, the advance in statistics and econometrics has facilitated their development and implementation, all of which have had a beneficial impact on EKC estimation. On the other hand, several studies have found evidence in favor of EKC, suggesting that some developing and transition economies have succeeded in attaining the income threshold, and have improved their environmental conditions. However, according to some works, the estimated value of the income turning point lies outside the sample range. In these specific cases, the findings should be treated with care, as this may imply that the future growth may increase pollution levels, and/or highlight possible issues regarding the EKC

and the associated threshold identification. Taken collectively, both the theoretical foundations and empirical evidence, could contribute to a better understanding of the pollution-growth nexus in the EKC context, and suggest some meaningful insights regarding the future works on the subject, as well as the crucial policy implication in developing and transition economies.

In light of the overall results, some policy implications could be drawn. First, some developing and transition states have managed to keep low levels of pollution along with economic growth, and even reached the EKC threshold for a lower level of income compared to developed nations (see e.g. the recent work of Yao et al., 2019, among others). Hence, these states could be treated as a positive example and examined more in detail to get insights related to the factors that contribute to inducing a bending downward curve in pollution. In this regard, over the years, the environmental and energy economics literature has unveiled some of the key elements that may promote a reduction in pollution levels (increase environmental quality). Focusing our attention primarily on developing and transition economies, we mention the factors related to energy structure, such as lower energy consumption, higher renewable and nuclear energy share in total energy consumption, higher energy efficiency (see e.g. Baek and Kim, 2013; Azlina, 2014; Sugiawan and Managi, 2016; Danish et al., 2017; Dong et al., 2018; Sinha and Shahbaz, 2018; Chen et al., 2019b), the factors associated to overall political system, such as good governance, corruption control, higher institutional quality, and political stability, and democracy (see e.g. Shahbaz et al., 2013; Osabuohien et al., 2014; Ozturk and Al-Mulali, 2015; Chen et al., 2018; Purcel, 2019; Ronaghi, 2019), the coexistence of an eco-friendly and relatively large industry sector and a high labor productivity which uphold complex techniques (see e.g. Lazăr et al., 2019), the environmental awareness (Chen et al., 2019a), among others. Besides, Halkos and Bampatsou (2018) revealed the importance that international agreements have on climate change mitigation. Their recent findings showed that the states which signed an international agreement, such as the Kyoto Protocol, exhibit higher environmental efficiency compared to their counterparts. These results are quite significant (all the more that their sample of 73 countries covered 55 developing ones) and may suggest that the developing world should be engaged more actively at international and also national level in green activities to ensure high environmental efficiency. Likewise, for transition economies, the findings of Zugravu-Soilita (2018) suggested that trade intensity in environmental goods reduced CO<sub>2</sub> emissions, primarily through the income effect. However, the opposite is found for water pollution, while for SO<sub>2</sub> emissions, the effect lacks significance.

Overall, the author argued that in the context of sustainable development, freer trade in environmental goods might be attained through the regional or bilateral agreements that reflect the countries' peculiar context.

Second, after a certain threshold is reached, environmental degradation may be irreversible and costly, both economically and socially (Munasinghe, 1999). Bearing in mind that the effects of policies and regulations are often visible in the long-term, to fight against environmental degradation, it is primordial to consider all the potential detrimental factors and take preventive measures. As such, good knowledge of the domestic economic, social, and political environment, along with a constant adaptation of environmental regulations and policies, may bring added value and improve the environmental quality. Furthermore, prolific international cooperation could foster the assimilation of know-how and new green technologies. Nowadays, as also stipulated by the Paris agreement, among other instruments, there is a need for developing and transition economies to become more involved in climate change activism and fight together with developed nations against the threats of global warming. Building on the present literature review, future work could be drawn upon a meta-analysis in order to better understand the pollution-growth nexus through the EKC incidence.

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