Environmental Science and Pollution Research (2022) 29:10091–10100
https://doi.org/10.1007/s11356-021-16161-x

RESEARCH ARTICLE

Assessment of major food crops production-based environmental efficiency in China, India, and Pakistan

Muhammad Shoaib Aslam [1] · Pan Huanxue [1] · Sidra Sohail [2] · Muhammad Tariq Majeed [3] · Saeed ur Rahman [4] · Shoaib Ahmad Anees [5]

Received: 22 May 2021 / Accepted: 21 August 2021 / Published online: 12 September 2021

Abstract

Global warming and food security have led to increasing concern about agricultural crop production efficiency, especially wheat and rice farming. The purpose of the current study is to measure wheat and rice production efficiency scores with environmental quality in China, India, and Pakistan by using a data envelopment analysis (DEA) model. The DEA results show that China and India are more efficient in wheat and rice production but it is not efficient in the environment in the study period. The results also show that Pakistan has also relatively small wheat and rice efficiency compared with China and India and increased the efficiency with the passage of time. The practical outcomes also show that Pakistan has the most efficient and effective states from the periods 2008 to 2019 in terms of wheat and rice efficiency and also a small increase in carbon emission. Based on the findings, policymakers should pay attention to the role of green technology in reducing agricultural CO2 emissions.

Keywords Wheat and rice efficiency · Environmental pollution · Data envelopment analysis

Introduction

Sufficient, healthy, and secure production of food for the fulfillment of needs of the worldwide population that has been estimated at 10 billion by the year 2015 is facing a challenge because of several abiotic and biotic dynamics affecting crop quality and output (Lyu et al. 2020). As highlighted by United Nations Food and Agriculture Organization, approximately 220 billion dollars of worldwide economic losses were recorded due to contamination of plants; however, epidemics of plants create approximately 20–40% losses in the worldwide production of crops (Cai and Yan 2019). These issues intensified due to emerging types of plant infections and epidemics, cultivatable land, shortage of supply of clean water, and climate variations (Tiep et al. 2021). The expansion of the sustainable production system of agriculture is stimulated to fulfill the Sustainable Development Goals of United Nations for improving the wellbeing of humans and ending hunger

Responsible Editor: Ilhan Ozturk

✉ Pan Huanxue
panhuanxue@126.com

✉ Sidra Sohail
sidrasohail_14@pide.edu.pk

Muhammad Shoaib Aslam
Shoaib.bjfu@gmail.com

Muhammad Tariq Majeed
tariq@qau.edu.pk

Saeed ur Rahman
srehman@gudgk.edu.pk

Shoaib Ahmad Anees
anees.shoaib@gmail.com

[1] School of Economics and Management, Beijing Forestry University China, Beijing, China

[2] Pakistan Institute of Development Economics (PIDE), Islamabad, Pakistan

[3] School of Economics, Quaid-i-Azam University, Islamabad, Pakistan

[4] Department of Economics, Ghazi University, Dera Ghazi Khan, Pakistan

[5] Beijing Key Laboratory of Precision Forestry, Forestry College, Beijing Forestry University, Beijing, China

with a minimum environmental cost. This expansion is needed in small farm holders and large-scale production systems in developing countries (Chuong 2020). Innovations in the technology sector should be adopted to deliver long-lasting solutions for production and environmental preservation for improved worldwide compliance and safety with SDGs (Sun et al. 2021).

The agricultural sector plays an important role in feeding the global population and helps the rural livelihood in the developing world. It also contributes 21% share in global CO_2 emission (Hafeez et al. 2020). Besides, it is regarded as the key driver of economic growth and development. The physiocracy school of thought has supported this view (Higgs 1897). This premise of the ideology as compared with other schools of thought such as mercantilism is reinforced in the literature by Bekun and Akadiri (2019) and Sertoglu et al. (2017). However, identifying the path for long-run gains has been an issue of intensive debate and interest among agriculture economists and policymakers. Particularly, whether gains from the agriculture sector or environmentally efficient or not has become an important research issue and policy concern across the globe.

Many studies have evaluated agricultural production efficiency and environmental efficiency at the farm level and at a national level. Suhariyanto and Thirtle (2001) for 18 Asian economies from 1965 to 1996; Nkamleu (2004) for 16 African economies over the period 1970–2001; Coelli and Rao (2005) for a global sample of 93 economies over the period 1980–2000; Blazejczyk-Majka et al. (2011) for 85 European Union (EU) regions over the period 1989–2007; Hermoso-Orzáez et al. (2020) for 28 EU countries over the period 2005–2012; Zamanian et al. (2013) for 27 the Middle East and North Africa (MENA) countries from 2007 to 2008; Anik et al. 2017 for four South Asian economies, namely, Pakistan, India, Bangladesh, and Nepal, from 1980 to 2013; Le et al. (2019) for nine east Asian economies over the period 2002–2010; Gatimbu et al. (2020) for Kenya over the period 2012–2016. These studies have provided mixed evidence. Further, heterogenous environmental efficiency scores are reported within a region or similar group of countries.

The increasing use of petroleum products in the agriculture sector is putting immense pressure on environmental quality and posing a threat to global emission targets decided in Kyoto protocol. Besides, agriculture practices such as the chemical products like fertilizer, pesticide, and crop nutrients are degrading environmental quality (Zhao et al. 2020; Palaniyandi et al. 2013). Further, the growing demand for food as a result of the increasing population is promoting unsustainable practices in the agriculture sector. In this situation, promoting sustainable agriculture development has become a global concern. Apparently, growing demand for food and sustainable agriculture development show a trade-off; however, enhancing agriculture productivity and efficiency can help to seek a balance between agriculture production and ecological performance.

Stolze et al. (2000) argued that agriculture can improve or degrade the environment depending upon the type of forming. In the case of organic farming, environment tends to improve because of low dependency on high energy-consuming feedstuffs and chemical fertilizers. Önder et al. (2011) found out that the agricultural process has a positive and negative impact on the environment. The positive impact generates from the provision of natural life and increasing the level of oxygen in the atmosphere by photosynthesis, while a negative impact is generated from pesticides, fertilizer, soil stubble burning, and plant hormone usage. Natural life has a positive and significant relationship with a sense of community (Li et al. 2021a, b; Zhao et al. 2020). Reynolds et al. (2015) analyzed the association between agricultural productivity and CO2 emissions for sub-Saharan African and South Asian countries. Their findings suggest that agricultural practices are negatively linked with emissions in both regions. Besides, their findings reveal that proper agricultural management systems, crop cultivation, and harvest system improve the environmental quality in the sampled countries. Furthermore, sustainable development enhances the environmental degradation by financial sector improvements for Belt and Road initiative (Li et al. 2021a, b; Hafeez et al. 2019; Hafeez et al. 2018).

The growing use of synthetic fertilizer is consistently increasing to fulfill the increasing demand for food at the cost of environmental quality. Ul Haq et al. (2020) explored the environmental efficiency of chemical fertilizer at tea farms in Rize Province of Turkey using DEA analysis. Their results reveal that tea growers are 32% "eco-inefficient" in the locality. Their estimates suggest that overuse of fertilizer at tea farms increases emissions by 289.3 kg/hectare of emissions. Thus, inefficient utilization of chemical fertilizer negatively contributes to environmental efficiency. Gatimbu et al. (2020) explored environmental efficiency of "small-scale tea processors" in Kenya using DEA approach over the period 2012–2016. Their study reveals that tea processors have 49% efficiency index suggesting that these processers are environmentally inefficient. Besides, the processors can reduce 51% of the environmentally harmful inputs without lowering tea production.

Hermoso-Orzáez et al. (2020) measure environmental efficiency for European Union member countries using DEA approach from 2005 to 2012. The findings of their study suggest that 14 countries demonstrate high environmental efficiency. Le et al. (2019) explored total factor productivity and environmental efficiency of the agriculture sector for nine east Asian economies over the period 2002–2010. They use "data envelopment analysis (DEA)" methods for empirical analysis. Their results reveal that total factor productivity decrease over the study period is mainly attributed to a decline in "technical efficiency," while the results for environmental efficiency are mixed for sampled economies. Taiwan, Japan, and Korea showed the highest scores for environmental efficiency of the agriculture sector while Thailand exhibited the lowest scores.

In this study, we focus on China, India, and Pakistan to evaluate the environmental efficiency of selected agriculture products and overall agriculture production. These economies comprise a large agricultural sector, which is a key source of employment and economic output (Aslam et al. 2021). Besides these countries are ranked as the top five populous countries of the world, and their demand for agriculture production to feed the large population has immense pressure on their agriculture sectors. Pakistan and India are neighbor countries, and the agriculture practices of one country have repercussions for other countries. For example, crop burning in India severely affects the air quality of Pakistan cities such as Lahore. Pakistan is also closely connected with China through socio-economic and political interaction. For example, China Pakistan Economic Corridor (CPEC) has wide reach implications for different sectors of both countries including the agriculture sector. China and India are among the global top producers of crops like rice, wheat, and cotton, and they also compete for agricultural production efficiency. Hence, a comparative analysis of agricultural productivity and environmental efficiency is needed at the present time.

The agriculture sector in China is growing rapidly owing to the adoption of the oil farming model. Agriculture production is growing 10.21% annually, and its value in 2017 was 618.1 billion Yuan (Li et al. 2020). Meanwhile, petroleum farming is considered an "anti-ecological" force undermining sustainable development practices in China. Further, negative external effects have produced many environmental concerns that have limited sustainability in the agriculture sector of China (Chen et al. 2015). The excessive use of fossil fuel-dependent machinery and chemicals are the main factors causing negative externalities (Li et al. 2021a, b; Luo et al. 2020; Sun et al. 2020). Carbon sequestration is helpful to control global warming and also maintains regional environmental stability (Shen et al. 2021; Shen et al. 2020).

India is the second-largest producer of wheat and rice. The agriculture sector in India is considered the main source of livelihood for more than 80% of the rural population, and its share in GDP is 15%. Each year India's rice farmers burn the stubble of the harvested paddy crop, contributing to the environmental loss. Such inefficient practices need an immediate response. Pakistan is largely dependent on the agriculture sector as agriculture comprises 23% of GDP and absorbs 37% of the labor force. The major crop of Pakistan is the cultivation of rice which contributes 6% of pollution emissions and 2.1% of emissions come from agricultural soil. These pollution emissions come from water mismanagement, inefficient fertilizer applications, and various agricultural activities that are responsible for higher pollution emissions. Most input of the agricultural sector is severely influenced CO2 emissions than other pollution indicators (Akbar et al. 2021; Rehman et al. 2021a, b); therefore based on previous literature, we used CO2 emissions variables for environmental efficiency. The share of wheat and rice is large in China, India, and Pakistan's total agricultural productivity. Therefore, we select only two products that consume more dirty inputs in production activities.

The aforementioned discussion implies that the extant literature on the environmental efficiency of the agriculture sector has certain caveats. First, the literature does not provide conclusive evidence on the environmental efficiency of the agriculture sector. Second, the literature mainly focuses on the overall productivity of the agriculture sector overlooking the significance of product-specific environmental efficiency of the agriculture sector. Third, the findings of empirical studies are sensitive to study samples, datasets, time span, and methodological frameworks. Fourth, the results are sensitive to country-specific agricultural practices. Fifth, the analysis of China, India, and Pakistan in a comparative setting in a single student is not available in the available literature.

For efficiency analysis, this study utilizes labour, land, fertilizer, pesticide, machinery, and irrigation as inputs, while rice, wheat, and agriculture gross output as outcomes. We extend the literature by evaluating wheat and rice production based on environmental efficiency in China, India, and Pakistan over the period 2008–2019. We have employed Data Envelopment Analysis (DEA) approach to estimate the results. The DEA approach of analysis has been supported by many studies; it is a flexible approach, facilitates evaluating comparative environmental efficiency, and is established as a sound method to assess the efficiency of environmental policies in a particular area, country, and region. Besides, this study also analyzes disparities, trends, and potentials for selected sampled countries.

This study has practical significance. The study facilitates evaluating comparative environmental efficiency and is established as a sound method to assess the efficiency of environmental policies in a particular area and country. It is expected that the findings of this research will offer appropriate policy implications to manage environmental efficiency and sustainable economic growth in Pakistan, India, and China and for economies having similar agricultural profiles. The research provides aid for policymakers and government officials to improve the agricultural production and environmental efficiency of the agricultural sector in China, India, and Pakistan. Our study is problem-oriented and important for the country in general, and to stakeholders working in the particular domain of agriculture and environment. The findings of this research are helpful for those economies which are prioritizing agricultural and environmental sectors in economies.

The remaining study is structured as follows: Section 2 reported the literature review. Section 2 provides a discussion on the method and model. The data description and sources are provided in Section 3. Empirical results and discussion are presented in Section 4. Finally, Section 5 provides the conclusion and policy implications.

Literature review

Since the industrial revolution, one of the primary sources of environmental pollution is the rising anthropogenic social and economic activities. Indeed the massive rise in CO2 emissions is a major threat to the environment, resulting in severe weather changes, melting of glaciers, rising sea level, floods, droughts, and other natural calamities (Majeed and Ozturk 2020). Global warming is not only a threat for developed economies but also for developing economies. In recent years, the relationship between economic growth and environmental has been extensively examined. In this perspective, Grossman and Krueger (1991) noticed an inverted U-shaped relationship between economic development and environmental quality, known as the Environmental Kunet Curve (EKC) hypothesis. This hypothesis proposed that during the early part of the development, the quality of the environment deteriorates due to excessive use of energy and other natural resources; however, at the later stage, as the per capita income rises and people's living standards improve, the demand for the clean environment (Sugiawan and Managi 2016). Most of the earlier studies, in this regard, have studied the EKC hypothesis in the presence of energy consumption and considered it as a primary driver behind environmental degradation (Al-Mulali et al. 2016; Alola and Ozturk 2021). Apart from the EKC hypothesis, the IPAT model of Ehrlich and Holdren (1971) also provides the foundation for capturing the impact of human actions on environmental quality and considered population as a primary determinant of environmental quality (Xu 2020). The rising population exerts extra burden on the environment by increasing the demand for urbanization, industrialization, energy, information and communication technology, tourism, etc. (Ullah et al. 2020; Chishti et al. 2020; Usman et al. 2021). The most crucial demand of the rising population is the demand for food; thus, the importance of the agriculture sector increased as it provides food to billion of people worldwide (Ozturk 2017; Rehman et al. 2020).

The agriculture sector relies heavily on the use of nonrenewable energy sources for producing vegetables and crops and growing livestock; thus, the contribution of the agriculture sector in total worldwide greenhouse gas (GHG) emissions have soared to 14–30% (Rehman et al. 2019). The agricultural sector needs energy for running equipment and machinery, irrigation purposes, feeding, and growing livestock (Chandio et al. 2020a, b Rehman et al. 2021a, b). Moreover, the agriculture sector also uses fertilizers made up of nitrogen, which emit a massive amount of CO2 emissions. According to Food and Agriculture Organization (FOA), the agricultural sector can reduce its current CO2 emissions by 80–88% (Reynolds and Wenzlau 2012). Efficient soil and crop management can help reduce a massive amount of CO2 emissions with the help of soil organic substances. This can be achieved by reducing tillage and non-tillage, altering land usage from farmed land to perpetual crops, and restoring damaged land (Paustian et al. 2016). A rise in the productivity of the agricultural sector may promote CO2 emissions and consequently trigger climate change (Chandio et al. 2020a, b).

Worldwide CO2 emissions produced by the agriculture sector is marginally less as compared wih the thermodynamics sector. Therefore, it becomes imperative to mitigate the level of agriculture-related CO2 emissions in the atmosphere by using agricultural methods and procedures that are less energy-intensive. Given the importance of low-carbon agriculture techniques and production methods, the application of such approaches has become the cornerstone of sustainable economic development goals (Nayak et al. 2015; Rehman et al. 2021a, b). Recently, empirics and policymakers started to focus on the agriculture sector as a potential determinant for environmental quality. However, the empirical literature is still at its infancy stage vis-à-vis agriculture-energy growth-environment nexus (Zhang et al. 2019; Baležentis et al. 2019).

Gokmenoglu and Taspinar (2018) tested the EKC hypothesis for Pakistan's agriculture sector over 1971–2014 and found support for the EKC hypothesis. They find evidence of two-way causality among energy consumption, GDP, added agricultural value, and CO2 emissions. Further, the study confirmed the positive inelastic impact of added agricultural value on CO2 productions. For Tunisia, Jebli et al. (2016) estimated the EKC hypothesis for the agricultural sector by adding renewable energy and trade openness variables. Their findings did not confirm the presence of EKC in the agricultural sector of Tunisia. They demonstrated the positive effects of agriculture on the CO2 emissions while the adverse impact of renewable energy on the CO2 emissions. This discovery recommends that introducing renewable energy in the agricultural sector increases its progress and decreases its CO2 releases. Likewise, Liu et al. (2017) were also not able to prove the existence of EKC in the agricultural sector of four Association of Southeast Asian Nations (ASEAN) countries. Conversely, Rafiq et al. (2016), by collecting data on the agriculture sector for 53 countries, confirmed the presence of the EKC hypothesis. Sarkodie and Owusu (2017) examined the influence of crop and livestock production on the carbon emissions of Ghana for the period 1961–2012. The study confirmed two-way causal effects between crops and CO2 releases. In contrast, their findings confirmed the evidence of one-way causality running from the livestock to CO2 emissions. More recently, Ridzuan et al. (2020) investigated the EKC hypothesis for Malaysia over the period 1978–2016 by integrating the variables of renewable energy, urbanization, and agriculture sub-sectors (crops, fisheries, livestock). The study confirmed the presence of the EKC postulate and supported the negative impact of crops, fisheries, and renewable energy on CO2 emissions. However, urbanization increased the CO2 emissions in Malaysia.

Method and data

Data envelopment analysis (DEA)

The study utilizes the DEA to evaluate the environmental efficiency in the agriculture sector for the three most important countries in the region, i.e., Pakistan, India, and China. A similar modeling approach is also adopted by Gatimbu et al. (2020) and Kuhn et al. (2020) for the environmental efficiency of small-scale tea and livestock farms. According to this method, in a simple framework, a firm uses two inputs to produce a single output under the condition of constant returns to scale (CRS). Rehman et al. (2021a, 2021b) noted that agriculture inputs as well productivity is dramatically changed the climate. However later one DEA approach is used in the case of many inputs and outputs. The main advantage of the DEA method is that they identify the sources as well as the amount of inefficiencies in included inputs and outputs for each country. Mostly, DEA method is used for calculating the technical and/or environmental efficiency of decision-making units (DMU). The DEA is proposed by Charnes et al. (1978), and the original model is also applicable with the assumption of CRS. DEA helps the researchers to segregate the desirable and undesirable inputs in the production process and thus gives robust results in assessing the environmental analysis for the respected DMUs.

Let us assume the vector of inputs is given as: $x = (x_1 + x_2, \ldots . x_k)$, vector of desirable output as $y = (y_1 + y_2, \ldots .,y_k)$, and the vector of undesirable output is as $u = (u_1 + u_2, \ldots . u_k)$. In addition, t is the production technology set which is given as under: $t = \{x, y, u\}$ where x inputs can produce desirable output y and undesirable output u. Production technology set t has the following assumption as suggested by Färe et al. (1989). Since the output is segregated into desirable or undesirable outputs, the assumption is stated as follows:

1) Bad or not usable outputs if $(x, y, u) \in t$ and $0 \le \theta \le 1$ therefore $(x, \theta y, \theta u) \in t$.
2) The joint null of undesirable and desirable outputs are as follows: if $(x, y, u) \in tu = 0$ then $y = 0$.

Assumption 1 represents undesirable or desirable outputs that are not usable or bad and it postulated that diminishing of not usable output is free or not unrestricted. In other words, we conclude from this postulation that rational diminution is possible. According to assumption 2, in the production process, it is equally possible that durable and undesirable outputs are produced. Consequently in order to curtail the undesirable outputs, we have to end the production process in t which is called production technology and mostly used in empirical research and sometimes named as environmental data envelopment analysis. The variation in inputs are also significantly captured by the DEA in output estimates.

Method to calculate environmental efficiency index

The prime objective of the study is to assess the wheat and rice production efficiency with CO2 emission efficiency in the case of three selected countries, Pakistan, India, and China for the time period 2008–2019. In order to calculate the environmental efficiency, we use the DEA method. In order to assess the wheat and rice environmental efficiency, we assume that there is j number of DMUs, i.e., $J = 1, 2, 3, \ldots, j$. As mentioned previously, these DMUs represent three different countries in the region, namely, Pakistan, India, and China. For each of the corresponding DMUj, we will have K number of inputs: $x_j = (x_{1j}, x_{2j} \ldots, x_{kj})$, M desirable outputs, and $y_j = (y_{1j}, y_{2j} \ldots ., y_{mj})$ and N undesirable outputs, $u_j = (u_{1j}, u_{2j} \ldots ., u_{nj})$. After determining the nature of these inputs, we will proceed in the following way. Here we assume the CRS that is depicted as follows:

$$\begin{array}{ll} \text{EEI} = \min\lambda & \\ ST \sum_{j=1}^{j} z_j x_{kk} \le x_k & k = 1, 2, 3, \ldots.., K \\ \sum_{j=1}^{j} z_j y_{mj} \ge y_m & m = 1, 2, 3, \ldots.., M \\ \sum_{j=1}^{j} z_j u_{nk} = u_k & u = 1, 2, 3, \ldots.., U \\ z_j \ge 0, & j = 1, 2, 3, \ldots\ldots J \end{array} \quad (1)$$

It is important to note that these expressions must meet all the properties on assumption 1, i.e., undesirable and desirable outputs are null joint and output are badly disposable (Al Asbahi et al. 2019).

Furthermore, in the above expressions, EEI stands for the environmental efficiency index. We obtain the EEI for each and every DMUs, and it postulates that the higher value of EEI will indicate the higher value of the environmental efficiency. We have calculated this EEI for every DMU in MS Excel program, by using the solver tool. We have consulted chapter 2 of "Data Envelopment Analysis: Modeling Operational Processes and Measuring Productivity" (Cook and Zhu 2008) for this purpose. However, we have modified these examples, which were given in the book, according to our needs. Since undesirable outputs are not included in the book's examples, therefore it is mandatory for us to change the restrictions to fit the model in the above equations.

Data

This study assesses the wheat, rice, and carbon emissions efficiency score of China, India, and Pakistan for the time period from 2008 to 2019. The data and period selection is based on the availability of the dataset. Previous studies also estimated the DEA model with a small sample size as Akbar et al. (2021). The key source of the dataset used in the analysis is the WDI Database provided by World Bank (2020). Five inputs and three outputs are used to measure the efficiency analysis of agricultural-environment models. We used the total CO2 emission of each country separately in the model. Four conventional inputs were adopted in this study, for instance, land, labor, consumption of fertilizers, and energy. Our study has chosen three outputs, wheat, rice, and carbon emissions. The detail of the description of the variable is also given in Table 1. The descriptive statistics of wheat, rice, and CO2 emissions of China, India, and Pakistan are given in Table 2. Desirable output changes in wheat are higher for China is 3.73% in 2014; 13.23% for India in 2017; and 8.16% for Pakistan in 2011. While output changes in rice are also higher for China is 3.18% in 2008; 9.68% for India in 2011; and 27.72% for Pakistan in 2011. China has a worse environmental quality situation because CO2 emissions are too high. As we observed in the data, India is also a high carbon emitter and Pakistan is a small producer of carbon in the environment.

Results and discussion

The evaluated results of wheat, rice, and CO2 emissions efficiency of the agriculture sector of China, India, and Pakistan countries are presented in Table 3. Technical efficiency scores were measured by using the DEA model with five inputs and three good outputs. The results exposed that China wheat efficiency values vary between 0.869 and 1.000, and rice efficiency varies between 0.908 and 1 in DEA analysis. China is more technically efficient in rice compared with wheat throughout the studied period. However, China has carbon emission efficiency scores that vary from 0.651 to 1, respectively. This finding infers that China is inefficient in the environment because wheat and rice production inputs are increasing environmental pollution. This may be credited to the expansion of un-clean agriculture inputs in the period of 2008–2019. In consequence, a robust increase in the environmental pollution in China.

As China is a more efficient economy in wheat and rice production. China mainly focuses on the fertilizer usage in wheat and rice and it also has undesirable output of carbon emissions. This finding is also consistent with Le et al. (2019), who noted that China had a huge amount of carbon emissions in East Asian economies because it is more use of energy. It also infers that excessive usage of unclean agricultural inputs is higher production and farmer profits, but it also adversely affects the environment. The high potential fertilizer savings also imply that the country failed to use fertilizers at optimal levels, which may be the result of deterioration of soil quality, ineffective farming management, and poor fertilizer quality. According to EUROSTAT (2015), an increase in nitrogen-based fertilizers could also aggravate GHG emissions in the agricultural sector. Our finding is also supported by Gatimbu et al. (2020), who noted that small-scale tea farmers in Kenya are still more environmentally inefficient and producing more CO2 emissions.

The other countries, i.e., India and Pakistan are found to be far below in wheat and rice score compared with China. India has the lowest scores of wheat and rice which are 0.752 and 0.781 in 2010. While India has also the lowest efficiency score of CO2 emission in 2010. The results also specified that India is also improving the wheat and rice production efficiency by using unfavorable input while keeping the environmental degradation in the economy more rapidly. Similarly, rice production in India has also emerged as a smog issue nowadays. The total cultivated areas used in agriculture are relatively larger than other countries and India had enabled to apply modern and smart technologies in agriculture, in adverse, which also emerge the environmental problems in the economy. Like fossil fuel, fertilizers and pesticide inputs are extensively used in wheat and rice

Table 1 Variable definitions

Variable	Definitions	Sources
Land input	Agricultural land (% of land area)	WDI
Labor input	Employment in agriculture (% of total employment) (modeled ILO estimate)	WDI
Fertilizer input	Fertilizer consumption (% of fertilizer production)	WDI
Energy consumption input	Fossil fuel energy consumption (% of total)	WDI
Wheat output	Wheat production (1000 tones)	WDI
Rice output	Rice production (tones)	WDI
CO2 emissions output	CO2 emissions (kt)	WDI

Table 2 Average (%) change of wheat and rice and CO2 emissions

Year	China			India			Pakistan		
	Wheat (Change, %)	Rice (Change, %)	CO2 (Kilotons 1000)	Wheat (Change, %)	Rice (Change, %)	CO2 (Kilotons 1000)	Wheat (Change, %)	Rice (Change, %)	CO2 (Kilotons 1000)
2008	2.62%	3.18%	7600	2.52%	2.40%	1600	2.05%	24.96%	159.0
2009	2.26%	1.72%	7600	2.42%	−8.35%	1700	0.83%	−1.00%	158.8
2010	0.27%	0.27%	8800	0.15%	6.11%	1700	−3.10%	−29.92%	169.4
2011	2.14%	2.77%	9700	7.51%	9.68%	1800	8.16%	27.72%	171.6
2012	3.30%	1.61%	10,000	9.22%	−0.06%	2000	−6.90%	−10.14%	170.1
2013	0.95%	−0.36%	10,000	−1.45%	0.89%	2000	3.14%	26.05%	174.8
2014	3.73%	1.48%	10,000	2.51%	−1.26%	2200	7.30%	0.35%	182.4
2015	3.36%	2.63%	10,000	−9.73%	−0.42%	2300	−3.44%	−2.88%	188.5
2016	0.48%	−0.49%	9900	0.55%	4.57%	2400	2.18%	0.71%	201.1
2017	0.80%	0.82%	11,000	13.23%	2.93%	2500	3.77%	8.77%	199.3
2018	-2.16%	−0.16%	12,000	1.38%	2.42%	2600	−5.64%	−3.33%	204.1
2019	1.64%	−0.03%	12,000	3.73%	2.77%	2800	−3.19%	0.42%	208.9

production. These all low and substandard quality inputs significantly raise the carbon emissions in India and reduce environmental quality. There are several reasons behind the difference in wheat and rice productivity and high carbon emission in the China and India nations, such as excessive input materials of agricultural productivity.

In Table 3, the results also show that Pakistan has a less efficient economy in wheat and rice among the other two economies, whereas China and India are more effective productivity scores of wheat and rice, respectively. It also observed that the wheat and rice productivity of Pakistan has been slightly improving from 2008 to 2019 and also increasing the environmental quality inefficacy by increasing the CO2 emissions in Pakistan. Findings also show that Pakistan is an efficient state in an environment with a score of CO2 emissions (0.026), whereas the less environmental quality states are namely China and India with CO2 emissions scores of 1.000 and 0.268 in 2019. The finding shows that the carbon emissions efficiency score has been increased with the time period. The results also show that the Pakistan efficiency scores CO2 varies from 0.019 to 0.026, and China has the highest scores among the economies. Pakistan has also a smog issue due to rice harvesting (Singh et al. 2020).

Moreover, it is worthy to note that the environmental quality efficiency of Pakistan is also better than China and India economies because of their small use of agricultural inputs in production activities (Aslam et al. 2021). In Pakistan, most farmers have preferred manual forming in the agricultural sector by using clean inputs due to small resources. Although China is starting green technology in the agricultural sector, its effects are not yet visible on the environment. However, China's agricultural economy has been grown rapidly due to the massive use of the oil farming model, which also enhances carbon pollution. At the current time, petroleum agriculture has also been emphasized and even adopted and it has "anti-ecological" effects in the process of promoting agricultural sector development. Indian agricultural sector has been moved into a new dimension and a severe agricultural growth phenomenon, India has also become one of the key carbon emitters in the globe.

Based on the findings, China is also a key carbon-emitter country and it has a large volume and share of agricultural production. China is also a leading position in terms of carbon emissions in Pakistan and India economies, but other economies have the lowest carbon emissions. This infers that China has efficiently captivated the carbon emissions from agricultural input in India and Pakistan countries. The carbon emissions of the agricultural, industrial, and service sectors of China are varied. There are various methods to control the negative externalities of agricultural inputs in production processes, and trends of carbon emissions are more severe in China and India.

Conclusion and policy recommendations

The chemical fertilizer and energy consumption ingredients are extensively used as production input for wheat and rice production in China, India, and Pakistan. However, the extra use of fertilizers and fossil fuel energy consumption is improving wheat and rice production but also adding environmental pollution to society. The extra use of unfriendly agricultural inputs not only contributes to the wheat and rice crop yield significantly but also positively contributes to carbon emissions. Therefore, the

Table 3 Wheat, rice, and CO2 emission efficiency of China, India, and Pakistan

	Year	Wheat		Rice		CO2	
		Rank	Efficiency	Rank	Efficiency	Rank	Efficiency
China	2008	14	0.869	14	0.908	11	0.651
China	2009	11	0.879	10	0.919	12	0.647
China	2010	12	0.878	11	0.916	10	0.746
China	2011	9	0.896	9	0.941	9	0.822
China	2012	8	0.926	7	0.957	6	0.847
China	2013	7	0.935	8	0.953	5	0.847
China	2014	6	0.973	6	0.973	4	0.851
China	2015	4	0.992	2	0.985	7	0.841
China	2016	3	0.995	5	0.977	8	0.829
China	2017	1	1.000	3	0.983	3	0.919
China	2018	5	0.982	4	0.979	1	1.000
China	2019	1	1.000	1	1.000	1	1.000
India	2008	20	0.776	20	0.878	24	0.173
India	2009	23	0.754	24	0.781	22	0.178
India	2010	24	0.752	23	0.826	23	0.178
India	2011	19	0.808	15	0.905	21	0.188
India	2012	13	0.871	18	0.892	20	0.206
India	2013	16	0.861	17	0.902	19	0.206
India	2014	15	0.866	21	0.875	18	0.223
India	2015	21	0.769	22	0.857	17	0.231
India	2016	22	0.765	19	0.887	16	0.237
India	2017	18	0.857	16	0.903	15	0.244
India	2018	17	0.862	12	0.915	14	0.251
India	2019	10	0.882	13	0.909	13	0.268
Pakistan	2008	35	0.257	32	0.069	36	0.019
Pakistan	2009	34	0.262	33	0.069	35	0.019
Pakistan	2010	36	0.257	36	0.049	34	0.021
Pakistan	2011	27	0.281	34	0.063	32	0.021
Pakistan	2012	33	0.262	35	0.057	33	0.021
Pakistan	2013	31	0.272	27	0.072	31	0.022
Pakistan	2014	28	0.281	30	0.071	30	0.022
Pakistan	2015	30	0.278	31	0.072	29	0.023
Pakistan	2016	26	0.285	29	0.071	27	0.025
Pakistan	2017	25	0.296	25	0.077	28	0.025
Pakistan	2018	29	0.281	26	0.074	26	0.026
Pakistan	2019	32	0.271	28	0.072	25	0.026

purpose of this empirical research is to determine the efficiency of wheat and rice crop with the efficiency of the environmental quality for the time period of 2008 to 2019. For this, we employed the China, India, and Pakistan sample dataset and use the DEA econometric approach.

The wheat and rice efficiency result signifies that China produces more wheat and rice output and it has more carbon emissions. This reflects that environmental inefficiency seems to be higher for China among the group and accessed the 0.651 scores in 2008 and 1.000 score in 2019. The India efficiency scores of wheat and rice are 0.882 and 0.909, while the carbon emission efficiency score is 0.268 in 2019 that differs between the two economies. We have found that wheat is produced more efficiently than rice in Pakistan, while carbon emission efficiency scores range from 0.019 to 0.026 and alleviate the environmental quality. The environmental quality of Pakistan is a reality better than China and India because it extends the value of the environmental efficiency scores. The result infers that China and India are expected to be more efficient in wheat and rice with a large change in carbon emissions patterns.

India and Pakistan are labor-abundant economies as compared with China. China and India should be further strengthened the technical innovation in the agricultural sector by mitigating CO2 emissions. The majorities of farmers use manual wheat and rice harvesting in India and Pakistan. Empirical results signify that efficiency improvements are possible in wheat and rice output by reduction of CO2 emissions. The authorities should reinforce the green technology to overwhelm agricultural pollution from non-point agricultural sources. China and India need to pay attention to the role of informatization in reducing agricultural sector environmental emissions. An ear of market-oriented wheat and rice production model should be established to avoid the production of environmental pollution. The government and policymakers must also make reform traditional methods of wheat and rice production. Another important policy implication is that the government should impose a tax on emitter's formers and provide subsidies on green technologies that guarantee environmental quality. Authorities also have access to cheaper and green funds for the purchase of environment-friendly agricultural technologies. The aforementioned grand strategies should be adopted for energy losses and process waste in the agricultural sector.

This empirical research has one important limitation. This study did not control other relevant factors in empirical analysis such as cotton, sugarcane, vegetables, and fruits. Futures empirical research should extend their framework to contain other crops, which may also improve general findings. A similar methodology further can be applied to conduct the analysis for other economies and adding more input factors in a regression model across the specific time period. The authors should conduct the empirical research by using the wheat and rice dataset of plant level in pollutant economies and also add the technology variable in the analysis.

Authors' contributions This idea was given by Muhammad Shoaib Aslam. Pan Huanxue, Muhammad Shoaib Aslam, Saeed ur Rahman, and Muhammad Tariq Majeed analyzed the data and wrote the complete paper, while Shoaib Ahmad Anees and Sidra Sohail read and approved the final version.

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

Declarations

Ethical approval Not applicable

Consent to participate I am free to contact any of the people involved in the research to seek further clarification and information

Consent to publish Not applicable

Competing interests The authors declare that they have no conflict of interest.

References

Akbar M, Hussain A, Akbar A, Ullah I (2021) The dynamic association between healthcare spending, CO2 emissions, and human development index in OECD countries: evidence from panel VAR model. Environ Dev Sustain 23(7):10470–10489

Al Asbahi AAMH, Gang FZ, Iqbal W, Abass Q, Mohsin M, Iram R (2019) Novel approach of Principal Component Analysis method to assess the national energy performance via Energy Trilemma Index. Energy Rep 5:704–713

Al-Mulali U, Solarin SA, Ozturk I (2016) Investigating the presence of the environmental Kuznets curve (EKC) hypothesis in Kenya: an autoregressive distributed lag (ARDL) approach. Nat Hazards 80(3):1729–1747

Alola AA, Ozturk I (2021) Mirroring risk to investment within the EKC hypothesis in the United States. J Environ Manag 293:112890

Anik AR, Rahman S, Sarker JR (2017) Agricultural productivity growth and the role of capital in South Asia (1980–2013). Sustainability 9(3):470

Aslam MS, Xue PH, Bashir S, Alfakhri Y, Nurunnabi M (2021) Assessment of rice and wheat production efficiency based on data envelopment analysis. Environ Sci Pollut Res 28:1–13

Baležentis T, Streimikiene D, Zhang T, Liobikiene G (2019) The role of bioenergy in greenhouse gas emission reduction in EU countries: An Environmental Kuznets Curve modelling. Resour Conserv Recycl 142:225–231

Bekun FV, Akadiri SS (2019) Poverty and agriculture in Southern Africa revisited: a panel causality perspective. SAGE Open 9(1): 2158244019828853

Blazejczyk-Majka L, Kala R, Maciejewski K (2011) Data Envelopment Analysis in Estimation of Technical Efficiency Change of Regional Agriculture Production EU, 1989-2007. J Mathe Syst Sci 1(1):1–12

Cai H, Yan T (2019) Technology efficiency or allocation efficiency: the inverse relationship in China's cereal production. China Agric Econ Rev 11:237–252

Chandio AA, Magsi H, Ozturk I (2020a) Examining the effects of climate change on rice production: case study of Pakistan. Environ Sci Pollut Res 27(8):7812–7822

Chandio AA, Ozturk I, Akram W, Ahmad F, Mirani AA (2020b) Empirical analysis of climate change factors affecting cereal yield: evidence from Turkey. Environ Sci Pollut Res 27(11):11944–11957

Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision making units. Eur J Oper Res 2(6):429–444

Chen ZM, Liu Y, Qin P, Zhang B, Lester L, Chen G, Guo Y, Zheng X (2015) Environmental externality of coal use in China: Welfare effect and tax regulation. Appl Energy 156:16–31

Chishti MZ, Ullah S, Ozturk I, Usman A (2020) Examining the asymmetric effects of globalization and tourism on pollution emissions in South Asia. Environ Sci Pollut Res 27(22):27721–27737

Chuong HN (2020) Determinants of efficiency in rice production of farmers in Viet Nam rural. Sci Technol Dev J Econ Law Manag 4: First. https://doi.org/10.32508/stdjelm.v4i2.623

Coelli TJ, Rao DP (2005) Total factor productivity growth in agriculture: a Malmquist index analysis of 93 countries, 1980–2000. Agric Econ 32:115–134

Cook WD, Zhu J (2008) Data envelopment analysis: modeling operational processes and measuring productivity. Create Space Independent Publishing Platform

Ehrlich PR, Holdren JP (1971) Impact of population growth. Science 171(3977):1212–1217

EUROSTAT (2015) Regional GDP in the European union in 2013. Luxemburg: EUROSTAT

Färe R, Grosskopf S, Lovell CK, Pasurka C (1989) Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach. Rev Econ Stat 71:90–98

Gatimbu KK, Ogada MJ, Budambula NL (2020) Environmental efficiency of small-scale tea processors in Kenya: an inverse data envelopment analysis (DEA) approach. Environ Dev Sustain 22(4):3333–3345

Gokmenoglu KK, Taspinar N (2018) Testing the agriculture-induced EKC hypothesis: the case of Pakistan. Environ Sci Pollut Res 25(23):22829–22841

Grossman GM, Krueger AB (1991) Environmental Impacts of a North American Free Trade Agreement. NBER Working Paper, (w3914)

Hafeez M, Chunhui Y, Strohmaier D, Ahmed M, Jie L (2018) Does finance affect environmental degradation: evidence from One Belt and One Road Initiative region? Environ Sci Pollut Res 25(10): 9579–9592

Hafeez M, Yuan C, Khelfaoui I, Sultan Musaad OA, Akbar W, Jie L (2019) Evaluating the energy consumption inequalities in the one belt and one road region: implications for the environment. Energies 12(7):1358

Hafeez M, Yuan C, Shah WUH, Mahmood MT, Li X, Iqbal K (2020) Evaluating the relationship among agriculture, energy demand, finance and environmental degradation in one belt and one road economies. Carbon Manag 11(2):139–154

Hermoso-Orzáez MJ, García-Alguacil M, Terrados-Cepeda J, Brito P (2020) Measurement of environmental efficiency in the countries of the European Union with the enhanced data envelopment analysis method (DEA) during the period 2005–2012. Environ Sci Pollut Res 27:1–25

Higgs H (1897) The Physiocrats: Six Lectures on the French Économistes of the 18th Century. Macmillan and Company, limited, New York

Jebli MB, Youssef SB, Ozturk I (2016) Testing environmental Kuznets curve hypothesis: The role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol Indic 60:824–831

Kuhn L, Balezentis T, Hou L, Wang D (2020) Technical and environmental efficiency of livestock farms in China: A slacks-based DEA approach. *China Econ Rev 62*:101213

Le TL, Lee PP, Peng KC, Chung RH (2019) Evaluation of total factor productivity and environmental efficiency of agriculture in nine East Asian countries. Agric Econ 65(6):249–258

Li N, Lin H, Wang T, Li Y, Liu Y, Chen X, Hu X (2020) Impact of climate change on cotton growth and yields in Xinjiang, China. Field Crop Res 247:107590

Li X, Li Z, Jia T, Yan P, Wang D et al (2021a) The sense of community revisited in Hankow, China: Combining the impacts of perceptual factors and built environment attributes. Cities 111:103108. https://doi.org/10.1016/j.cities.2021.103108

Li X, Yu Z, Salman A, Ali Q, Hafeez M, Aslam MS (2021b) The role of financial development indicators in sustainable development-environmental degradation nexus. Environ Sci Pollut Res:1–12

Liu X, Zhang S, Bae J (2017) The impact of renewable energy and agriculture on carbon dioxide emissions: investigating the

environmental Kuznets curve in four selected ASEAN countries. J Clean Prod 164:1239–1247
Luo J, Li M, Liu X, Tian W, Zhong S et al (2020) Stabilization analysis for fuzzy systems with a switched sampled-data control. J Franklin Inst 357(1):39–58. https://doi.org/10.1016/j.jfranklin.2019.09.029
Lyu Y, Zhang X, Yang X, Wu J, Lin L, Zhang Y, Wang G, Xiao Y, Peng H, Zhu X, Yu X (2020) Performance assessment of rice production based on yield, economic output, energy consumption, and carbon emissions in Southwest China during 2004–2016. Ecol Indic 117:106667
Majeed MT, Ozturk I (2020) Environmental degradation and population health outcomes: a global panel data analysis. Environ Sci Pollut Res 27(13):15901–15911
Nayak D, Saetnan E, Cheng K, Wang W, Koslowski F, Cheng YF, Zhu WY, Wang JK, Liu JX, Moran D, Yan X, Cardenas L, Newbold J, Pan G, Lu Y, Smith P (2015) Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. Agric Ecosyst Environ 209:108–124
Nkamleu GB (2004) Productivity growth, technical progress and efficiency change in African agriculture. Afr Dev Rev 16(1):203–222
Önder M, Ceyhan E, Kahraman A (2011) Effects of agricultural practices on environment. Biol Environ Chem 24:28–32
Ozturk I (2017) The dynamic relationship between agricultural sustainability and food-energy-water poverty in a panel of selected Sub-Saharan African Countries. Energy Policy 107:289–299
Palaniyandi SA, Yang SH, Zhang L, Suh JW (2013) Effects of actinobacteria on plant disease suppression and growth promotion. Appl Microbiol Biotechnol 97(22):9621–9636
Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P (2016) Climate-smart soils. Nature 532(7597):49–57
Rafiq S, Salim R, Apergis N (2016) Agriculture, trade openness and emissions: an empirical analysis and policy options. Aust J Agric Resour Econ 60(3):348–365
Rehman A, Chandio AA, Hussain I, Jingdong L (2019) Fertilizer consumption, water availability and credit distribution: Major factors affecting agricultural productivity in Pakistan. J Saudi Soc Agric Sci 18(3):269–274
Rehman A, Ma H, Ozturk I (2020) Decoupling the climatic and carbon dioxide emission influence to maize crop production in Pakistan. Air Qual Atmos Health 13(6):695–707
Rehman A, Ma H, Ahmad M, Ozturk I, Chishti MZ (2021a) How do climatic change, cereal crops and livestock production interact with carbon emissions? Updated evidence from China. Environ Sci Pollut Res 28:1–12
Rehman A, Ulucak R, Murshed M, Ma H, Işık C (2021b) Carbonization and atmospheric pollution in China: The asymmetric impacts of forests, livestock production, and economic progress on CO2 emissions. J Environ Manag 294:113059
Reynolds L, Wenzlau S (2012) Climate-friendly agriculture and renewable energy: working hand-in-hand toward climate mitigation. Retrieved from www.renewableenergyworld.com; http://www.renewableenergyworld.com/articles/2012/12/climatefriendlyagriculture-and-renewable-energy-workinghand-in-handtoward-climatemitigation.html
Reynolds TW, Waddington SR, Anderson CL, Chew A, True Z, Cullen A (2015) Environmental impacts and constraints associated with the production of major food crops in Sub-Saharan Africa and South Asia. Food Sec 7(4):795–822
Ridzuan NHAM, Marwan NF, Khalid N, Ali MH, Tseng ML (2020) Effects of agriculture, renewable energy, and economic growth on carbon dioxide emissions: Evidence of the environmental Kuznets curve. Resour Conserv Recycl 160:104879
Sarkodie SA, Owusu PA (2017) The relationship between carbon dioxide, crop and food production index in Ghana: By estimating the long-run elasticities and variance decomposition. Environ Eng Res 22(2):193–202
Sertoglu K, Ugural S, Bekun FV (2017) The contribution of agricultural sector on economic growth of Nigeria. Int J Econ Financ Issues 7(1):547–552
Shen X, Liu B, Jiang M, Lu X (2020) Marshland Loss Warms Local Land Surface Temperature in China. Geophys Res Lett 47(6):n/a–n/a. https://doi.org/10.1029/2020GL087648
Shen X, Jiang M, Lu X, Liu X, Liu B, Zhang J, Wang X, Tong S, Lei G, Wang S, Tong C, Fan H, Tian K, Wang X, Hu Y, Xie Y, Ma M, Zhang S, Cao C, Wang Z (2021) Aboveground biomass and its spatial distribution pattern of herbaceous marsh vegetation in China. Scie China Earth Sci 64:1115–1125. https://doi.org/10.1007/s11430-020-9778-7
Singh R, Yadav DB, Ravisankar N, Yadav A, Singh H (2020) Crop residue management in rice–wheat cropping system for resource conservation and environmental protection in north-western India. Environ Dev Sustain 22(5):3871–3896
Stolze M, Piorr A, Häring AM, Dabbert S (2000) Environmental impacts of organic farming in Europe. Universität Hohenheim, Stuttgart-Hohenheim
Sugiawan Y, Managi S (2016) The environmental Kuznets curve in Indonesia: Exploring the potential of renewable energy. Energy Policy 98:187–198
Suhariyanto K, Thirtle C (2001) Asian agricultural productivity and convergence. J Agric Econ 52(3):96–110
Sun H, Mohsin M, Alharthi M, Abbas Q (2020) Measuring environmental sustainability performance of South Asia. J Clean Prod 251:119519
Sun H, Ikram M, Mohsin M, Abbas Q (2021) Energy security and environmental efficiency: evidence from OECD countries. Singap Econ Rev 66(02):489–506
Tiep NC, Wang M, Mohsin M, Kamran HW, Yazdi FA (2021) An assessment of power sector reforms and utility performance to strengthen consumer self-confidence towards private investment. *Econ Anal Policy 69*:676–689
Ul Haq S, Boz I, Shahbaz P, Yıldırım Ç (2020) Evaluating eco-efficiency and optimal levels of fertilizer use based on the social cost and social benefits in tea production. Environ Sci Pollut Res 27(26):33008–33019
Ullah S, Ozturk I, Usman A, Majeed MT, Akhtar P (2020) On the asymmetric effects of premature deindustrialization on CO2 emissions: evidence from Pakistan. Environ Sci Pollut Res 27(12):13692–13702
Usman A, Ozturk I, Ullah S, Hassan A (2021) Does ICT have symmetric or asymmetric effects on CO2 emissions? Evidence from selected Asian economies. Technol Soc 67:101692
World Bank (2020) World development indicators 2019. World Bank Publications
Xu C (2020) Determinants of carbon inequality in China from static and dynamic perspectives. J Clean Prod 277:123286
Zamanian GR, Shahabinejad V, Yaghoubi M (2013) Application of DEA and SFA on the Measurement of Agricultural Technical Efficiency in MENA Countries. Int J Appl 3(2):43–51
Zhang L, Pang J, Chen X, Lu Z (2019) Carbon emissions, energy consumption and economic growth: Evidence from the agricultural sector of China's main grain-producing areas. Sci Total Environ 665:1017–1025
Zhao C, Zhong S, Zhang X, Zhong Q, Shi K (2020) Novel results on nonfragile sampled-data exponential synchronization for delayed complex dynamical networks. Int J Robust Nonlinear Control control 30(10):4022–4042. https://doi.org/10.1002/rnc.4975