




A systematic literature review of data envelopment analysis implementation in agriculture under the prism of sustainability

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Abstract

Safeguarding natural resources and energy is essential to ensure food security for future generations. Given the increase of published papers in the agricultural field applying Data Envelopment Analysis (DEA), this review seeks to address the special requirements of this methodology when implemented in the agricultural sector as well as to classify papers under sustainability aspects (economic, environmental, social). More specifically, 120 papers from Scopus and Web of Science databases were included in this review by using PRISMA methodology, and they were tested in the following groups (i) General information, (ii) DEA implementation, (iii) DEA extensions, (iv) Data type, (v) Data collection and processing, and (vi) Sustainability dimensions. Results indicate that there is a great need for weights use when performing DEA in the agricultural sector, to acquire results with greater explanatory power. Moreover, systematic data collection of multiple factors could lead to the implementation of complex methodologies, providing feasible solutions to the involved stakeholders. Lastly, the social aspect is the least represented dimension out of the three aspects of sustainability, indicating the need for the integration of social factors in such analyses, especially when DEA is used to create a policy framework in a specific area.

Keywords Data envelopment analysis · DEA · Agriculture · Efficiency · Sustainability · Review

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1 Introduction

Food security, overpopulation, and conservation of natural resources are the biggest challenges for today's agriculture (Calicioglu et al. 2019). In addition, the global trend towards adopting Sustainable Development Goals (SDGs) (United Nations 2015) has not left the agricultural sector unaffected, as the same principles will have to be integrated into this sector for (United Nations 2015) sustainable agriculture (European Commission 2015).

Although the search for «sustainability» term shows a slight increase from 2014 to 2021 for general Google users, there is a rapid increase in searching for the term in the academic community of 160% for the same period, verifying the effort of researchers to find solutions or methodologies to achieve the globally accepted sustainable development goals (Google Trends 2021). Taking into consideration the need to provide food for an ever-growing population with an inexhaustible number of available resources, leads humanity to the establishment of new systems or the invention of new technologies which can produce the same amount of output using the least possible energy and resources. In other words, for ensuring sustainability in agriculture, the efficiency of existing systems needs to be increased. On operational terms, this means that either production levels should remain at the same levels with the need for inputs to be decreased, or output should be increased, given the inputs used. With this goal reassurances can be provided that future generations will have equal opportunities to access energy and natural resources.

Following the above line of reasoning, efficiency analyses can contribute to quantifying losses and highlight weak points on production processes in the agricultural sector, to minimize the exploitation of natural resources while producing adequate amounts of feed and food. Efficiency measurement can be achieved by using either parametric (e.g. Stochastic Frontier Approach -SFA (Aigner et al. 1977)) or non-parametric approaches such as DEA (Charnes et al. 1978). SFA is capable of distinguishing noise from inefficiency, however, DEA includes noise in its final results (Lampe and Hilgers 2015). Moreover, SFA is not so sensitive to outliers as DEA, due to the fact that SFA is based on regression models, while DEA computations are based on linear programming principles. Removal of outliers is a crucial stage for data preparation when performing DEA, which may end up in a false interpretation of the results if neglected (Sarkis 2007). On the other hand, DEA is mostly used in the agricultural sector, due to the fact that it can handle multiple inputs and outputs, in contrast with conventional SFA models, which can handle single input or output and multiple inputs or outputs. DEA also does not need any prior assumption about inputs and outputs relationship, compared with SFA, a decision that may lead to uncertain results (Watto and Mugeru 2019).

In order to assess the way that efficiency measurement is applied in the agricultural sector, VOSViewer software (Waltman and van Ecken 2010) was used. More precisely, Fig. 1 presents efficiency and agriculture results from the most cited papers of Scopus (first 2,000) and Web of Science (WoS) (first 1,000) databases.

DEA, which can perform efficiency evaluation in different stages of a production process, rather than considering only the initial inputs and final outputs. For instance, production and distribution are two main processes until the products will reach to final stores. By using Network DEA it is possible to optimize the procedure in each stage, without considering the whole system as a black box (Färe et al. 2007; Sarkhosh-Sara et al. 2020). Bootstrap DEA can create replicate datasets in order to check the standard error of their final outcomes (Bogetoft and Otto 2011), a meaningful technique for agriculture which deals with high variability of the involved factors or small samples (Tetteh Anang et al. 2020). Fuzzy DEA model is another approach where the integrated values are not constant, but they are varying within a range, quantifying the risk of the final decisions. Hatami-Marbini et al. (2011) in their literature review paper are presenting different approaches on how imprecise data can be handled under fuzzy concept, while Houshyar et al. (2012) have performed a Fuzzy DEA model so as to assess the sustainability performance of corn farmers. Lastly, Window DEA can be used for measuring efficiency through the use of time-series data. For instance, Pishgar-Komleh et al. (2021) assessed the eco-efficiency of the agricultural sector of European countries for 2008–2017 time period by using the Window DEA method. It should be stated that all the afore-mentioned approaches can handle undesirable outputs (e.g. greenhouse gas emissions) when estimating efficiency scores (Halkos and Petrou 2019), a significant characteristic for considering negative externalities to the environment or human health in the optimization process. Taking all the above mentioned into consideration, this study seeks to address the ways that DEA methodologies are implemented under the prism of sustainability in the agricultural sector.

The study proceeds as follows. Section 2 provides an overview of similar literature reviews in the energy and agricultural sector, clarifying the contribution of this paper. Section 3 presents the overall process of paper collection and screening. Section 4 presents general information of the included papers; DEA model implementation; DEA extensions; Data types used in DEA model; Data collection and processing and sustainability dimensions represented through DEA implementation. Section 5 provides further insights into the acquired results, proposing possible combinations with already existing papers, while in Sect. 6 proposals for future surveys are being made.

2 State of the art

The literature review of Zhou et al. (2018) is a crucial reference point, regarding DEA implementation under the sustainability term, indicating the chronological connection of published papers and the key points of DEA evolution from 1996 to 2016, reviewing 320 publications in total. The main conclusions of this study can be summarized as followed (1) Integration of undesirable or bad output in DEA, (2) Interaction of all three aspects of sustainability and the lack of social factor inclusion, (3) Results in adoption from enterprises and policymakers. Another literature review of Mardani et al. (2018), having reviewed 145 articles on the environmental and energy field, concludes that there is a need for further assessment

of methodological aspects relative to DEA. Big data, uncertainty, and heterogeneity of the involved DMUs are the main areas that DEA methodology should be further expanded to deal with the complex environment of the energy sector (T. Xu et al. 2020). Tsaples and Papathanasiou (2021) underline also the need for social inclusion, when performing DEA for sustainability. Moreover, on the same survey, it is highlighted that there is a misconception between eco-efficiency and sustainability term, while some authors use more dimensions, apart from economic, environmental, and social, like innovativeness or technology adoption.

The above-mentioned surveys have assessed DEA implementation in Energy and Environmental sectors in total. Considering the idiosyncrasies of the agricultural sector, due to the interaction of multiple factors such as biotic and abiotic environment, cultivation protocols, and applied agricultural practices, including the incorporation of sustainability principles, a literature review of 120 papers was conducted, considering the year after SDGs' release as a reference point for further promoting sustainability principles in the agricultural operational research society. Although Streimikis and Saraji (2021) have recently published a literature review for DEA in agriculture, focusing on the research gaps and main conclusions of each survey of undesirable outputs, the present review aims to contribute on the following questions:

- (1) What are the methodological gaps and the future research proposals?
- (2) How are the data collected and analyzed?
- (3) What are the methodologies combined or compared with DEA results?
- (4) Which of the three pillars of sustainability are covered through published papers or conference proceedings for application of DEA in agriculture?

3 Material and methods

To achieve the aim of this paper, a systematic literature review has been performed through the Scopus and Web of Science (WoS) database, using PRISMA guidelines (Page et al. 2021). More precisely, for this survey terms of «efficiency», «agriculture» and «sustainability» were used. Title, summary, or keywords were the main areas in which the above terms should be present to be included in this research. Due to a large number of acquired results ($n=6,960$ –Scopus and $n=7,237$ –WoS) and the fact that this paper focuses on DEA implementation, the «efficiency» term was replaced with «DEA» term, leading to 75 results from Scopus and 203 from WoS. Given the fact that this literature review assesses the ways in which DEA is applied in agriculture, under the prism of sustainability, a term which was highly promoted after the SDGs' release in 2015 (United Nations 2015). Having this as a reference point the period 2016–2022 was selected to be further analysed, leading to a number of 180 unique articles or conference proceedings (Fig. 2). Significant academic efforts prior to the selected years have been made in this field (Gerdessen and Pascucci 2013; Reig-Martínez et al. 2011; Zahm et al. 2008), thus this review seeks to capture the contribution of agricultural operational research to sustainability aspects after the year 2016, where there was a rapid increase of publications as Fig. 3 presents.

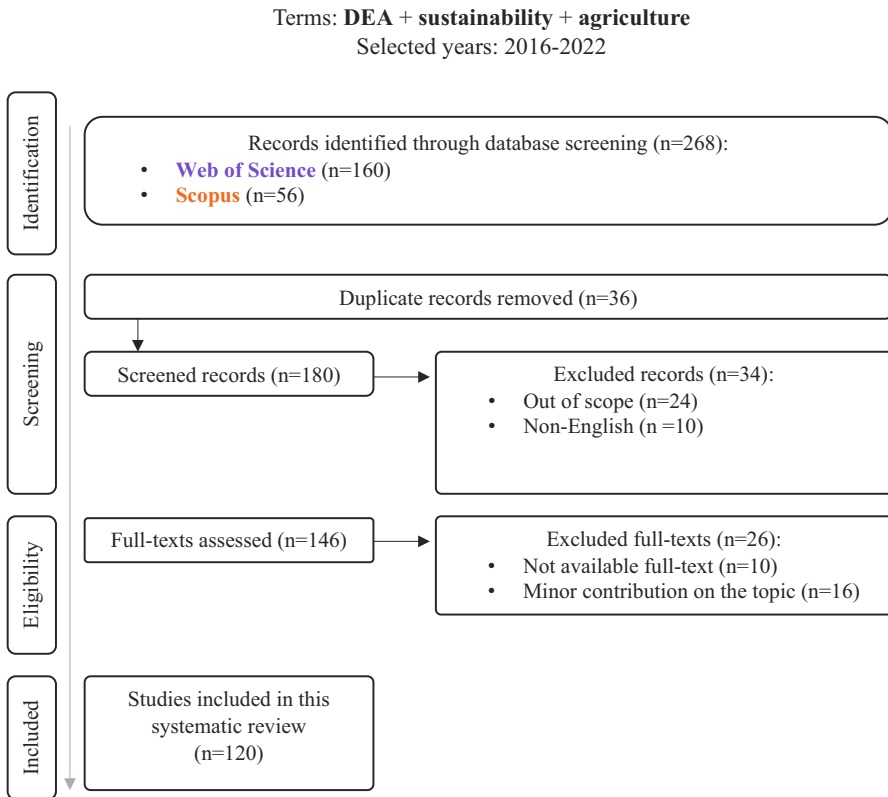


Fig. 2 Literature review methodology under PRISMA guidelines

References were exported on September 9th, 2022. Further screening was performed for removing duplicates and clarifying the content of the included papers. Out of 180 unique records, 34 of them were removed from the first stage due to the fact that 24 papers were not relevant to this literature review (mainly because they were referring in their abstract to the term «agriculture» as a part of an example or as a future implementation) and 10 of them were non-English papers. On the eligibility phase, 26 papers were excluded, 10 of them due to unavailability of full text and 16 of them due to minor contribution on the topic, meaning that in most cases agricultural sector was compared with other sectors mostly in national level but without deepening on agriculture. Based on the above-mentioned process, 120 papers were included in this systematic literature review. Out of the entire set of examined for this review, 116 were journal articles, accounting for 97% of the total, while the remaining 3% were conference papers.

Moreover, a detailed table of criteria, prior to the detailed review of each paper, was constructed based on the authors' experience in the field. As shown in Table 1, 23 variables were evaluated in each paper. More specifically, the selection of the variables was made to capture the overall picture of the DEA applicability in

agriculture under the prism of sustainability, but also to highlight the points that need further amelioration, or better integration of new methodologies from other scientific fields.

The above-mentioned data provide further insights on the given dataset of references, leading to the fulfillment of the goals set in the State-of-the-Art section.

4 Results

All categories of variables listed in Table 1 are presented in the same order in this section

4.1 General information

Regarding publication year, Fig. 3 presents that there is a noteworthy increase from 2016 to 2022. Apart from year 2020, which was the first year of COVID-19 pandemic, there is an additional amount of publications each year leading to an almost quadrupling of annual publications between 2016 and 2022, signifying there is a great deal of academic interest in this topic.

Table 2 contains the number of reviewed papers by source type, referring to 65 out of 120 papers (54%). *Sustainability*, *Journal of Cleaner Production*, *Science of the Total Environment and Agriculture* were the sources out of which the most papers were extracted for this review.

Due to the fact that DEA considers all the involved DMUs as homogenous, it was important to focus more on the geographical aspect of these applications. It is assumed that increased locality of application fits better to the characteristics of

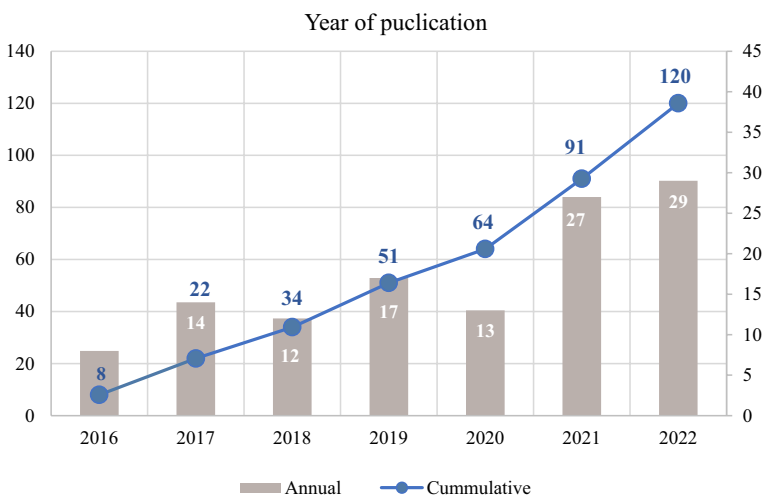


Fig. 3 Year of publication

Table 1 Examined data through the literature review process

Category	No.	Element	Description
1. General information	1	Author(s)	(-)
	2	Year	Year of publication
	3	Level	Application-level: International, National, Prefecture, Local
	4	Document Type	Journal article, Conference paper, Proceedings, etc
	5	Source Type	Journal name
	6	Inputs	Type of variables used as inputs
	7	Outputs	Type of variables used as outputs
2. DEA Implementation	8	Application system	Description of application system
	9	Approach	Input-oriented, Output-oriented
	10	DEA Model	Used DEA Models (VRS, CRS, SBM; Window etc.)
3. DEA Extensions	11	Undesirable Output	Use and Type of undesirable output
	12	Homogeneity/Weights	If all DMUs have been treated as homogenous
	13	Combination	Use and Type of any combined methodology with DEA
4. Data Type	14	Comparison	Use and Type of any methodology used to compare DEA results
	15	Qualitative data	Use of qualitative data
5. Data collection and processing	16	Timeseries	Use of data for a longer period than one year
	17	Geographic information system (GIS) Incorporation	Incorporation of GIS information in DEA model
	18	Source of Dataset	Personal interviews, Public or Private Datasets,
	19	Total Sample	Number of DMUs
	20	Sample equation	Followed methodology for defining sample size
6. Sustainability Dimensions	21	Software	Which software has been used for DEA implementation
	22	Sustainability Dimensions (in the DEA process)	Which of the 3 aspects of sustainability are assessed in the DEA model
	23	Sustainability Dimensions (in the total paper)	Which of the 3 aspects of sustainability are assessed in the whole paper's contribution

Table 2 Number of included papers by source type

No.	Source type	Number of included papers
1	Sustainability	29
2	Journal of Cleaner Production	9
3	Science of the Total Environment	4
4	Agriculture	4
5	Energies	3
6	Agricultural systems	3
7	Land Use Policy	3
8	Environmental Science and Pollution Research	2
9	Energy	2
10	Information Processing in Agriculture	2
11	Applied Energy	2
12	Energy for Sustainable Development	2

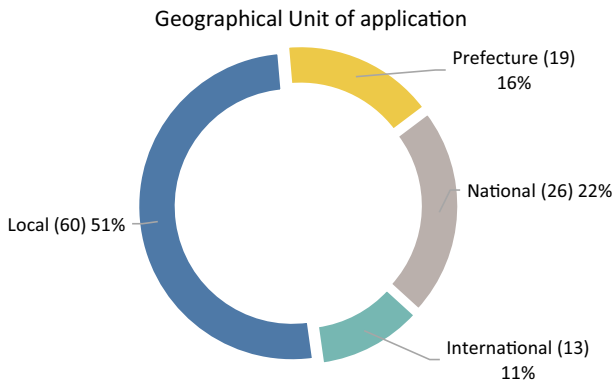


Fig. 4 Geographical unit of application

the model, mitigating the influence of different external factors. Figure 4 presents that the greatest part of papers (51%) is performed on a local, or regional level. Local level refers to surveys held inside the boundaries of a prefecture, prefecture label refers to the implementation of the survey between neighboring prefectures, national label refers to the inclusion of the majority of prefecture inside a country and lastly, international label refers to the comparison of agricultural sectors between different countries. It should be noted that in this figure 118 papers are included, because the remaining two are review papers.

Regarding the application system, Fig. 5 presents that a great part of the examined papers are referring to the agricultural sector in general, 38% implements

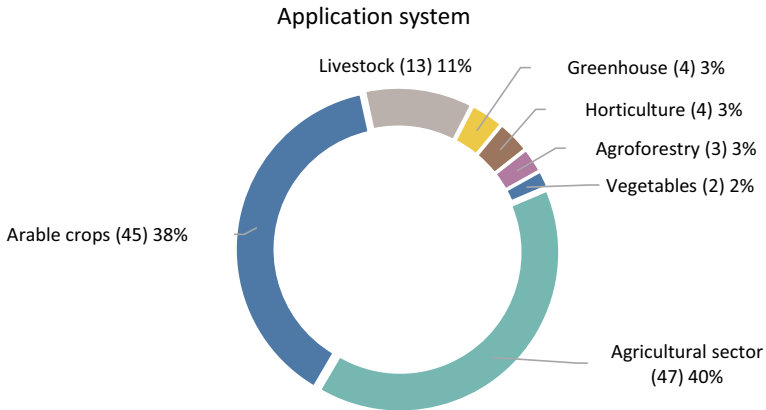


Fig. 5 Application system

optimization models for arable crops and a small part is referring to livestock, greenhouse products, fruits, timber and vegetables.

Table 3 (Appendix section) provides an overall view of included papers in this review. More particularly, author, year, application level, type of inputs and outputs as well as the specification of the application are presented.

4.2 DEA implementation

Regarding the selected approach, 76% used an input-oriented approach, 20% used an output-oriented approach, 2% compared the approaches of both results, and 2% did not specify the approach used.

Examining the use of DEA models in agriculture, it is evident that most of the obtained results were acquired using typical DEA models like CCR (CRS) and BCC (VRS). Particularly, as shown in Fig. 6, almost half of the examined papers (46%) are using both CRS, VRS and Scale efficiency, 23% used only VRS model (27 papers) and 9% used only CRS model (11 papers). Although the selection of the CRS or VRS approach is problem specific, in agricultural sector VRS assumption is preferred, due to the fact that the increase of inputs does not mean necessarily that this will lead to a proportional increase of outputs. In other words, doubling inputs (e.g. fertilizer) does not ensure double production in the end of the cultivation year. CRS scores are mainly extracted for scale efficiency calculations.

Additionally, Slack-based model (SBM) was used from 9 papers. As mentioned in the Introduction section, SBM models are used to provide accurate estimations of target values of each variable enabled in the DEA model. Debbarma et al. (2021) used SBM model to elucidate Iranian farmers' efficiency under the consideration of GHG emissions as undesirable output, while same model was used from Tian et al. (2016) for open-field grape production. Bootstrap DEA was used in 5 cases with a view to minimize the stochastic errors by producing replicate datasets. For instance,

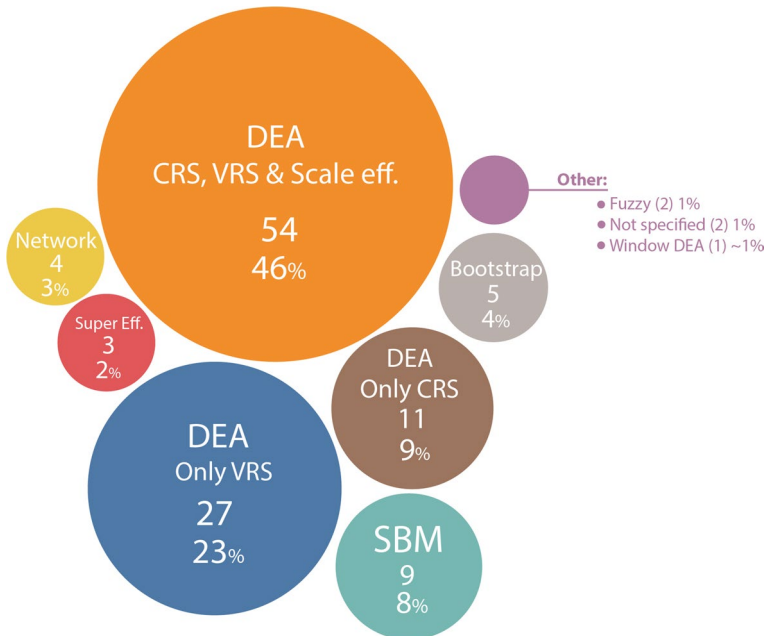


Fig. 6 Results of DEA models used

Nodin et al. (2022) have created 3,000 replicate datasets of rice producers to assure the reliability of acquired results. Super efficiency was performed by 3 papers or 2% of total sample. Cecchini et al. (2021) used this approach for minimizing the influence of extreme values to their final results when implementing an efficiency assessment on Italian sheep farms.

Network DEA was also implemented from 5 papers in order to reveal causes of inefficiency in different sub-systems of an overall process. Saputri et al. (2019) performed this methodology to assess the efficiency between the three distinct stages of agri-food supply chain (agricultural production, processing, transportation) for Indonesian rice producers. Kord et al. (2022) presented agricultural activity as two different stages (environmental and economic) and by using shared inputs between the two stages they performed a sustainability assessment for Iranian regions. Lu et al. (2022) have created a three stage Network model for assessing agricultural food production systems of EU countries under circular economy principles, meaning that the final output was acting as a carry over the next period.

Fuzzy DEA and Window DEA were the least presented methodologies of this sample referring to only 3% cumulatively. Mu et al. (2018) have assessed 55 dairy farms setting a range of -20 to $+20$ of their given values, so as to incorporate the uncertainty in their Fuzzy DEA model. Window DEA was used from Masuda (2019) to minimize the effects of global warming and eutrophication in rice production for 2005–2011 time period. Lastly, it should be mentioned that the followed methodology was not specified in 2 papers and the review papers (2) are excluded from this review process.

Regarding the comparison of the acquired results, only two surveys have proceeded to this step. W Kamal and Ilmas (2017) have compared their DEA results with SFA concluding that SFA technical efficiency results were higher than the ones of DEA, attributing this to bias correction of the SFA model. Khanjarpanah et al. (2017) implemented 2 types of cross-efficiency DEA models (aggressive and benevolent) to assess switchgrass cultivation in Iran and they proposed a third one additional model which contributes to a fairer optimization process.

Undesirable outputs impact assessment is another significant factor towards the achievement of sustainable development in agriculture, mainly by focusing on reducing their impacts on the environment, or trying to create a circular path. For these reasons, 25% (30 papers) used undesirable outputs in total. Most of them were using either Greenhouse Gas Emissions (GHG) as a total or applying CO₂ emissions only and this may be due to easy data accessibility. Lamkowsky et al. (2021) has also used N surplus indicator as undesirable output in Dutch dairy farms, a variable which has not been detected in crop production systems at all (e.g. N leaching). Additionally, Tang et al. (2022) included farm-specific undesirable variables such as soil erosion rate and grey water footprint in their DEA model, a characteristic that was absent from the other surveys. It should be noted that Grassauer et al. (2021) and Rybaczewska-Błazejowska and Gierulski (2018) included LCA results as inputs in their DEA models in order to minimize the environmental effects of agricultural productivity.

As stated in the general information section, there is an assumption of homogeneous examined units when performing DEA. Especially in the agricultural sector, which has a great variability both of abiotic (temperature, humidity, precipitation, type of soil etc.) and biotic environment (cultivar, variety, pests etc.) as well as the interaction between them, use of different weights is essential for setting an equal starting point for all DMUs involved. None of the included references has implemented any methodology that would make a fairer evaluation, a crucial point when considering equality on the agricultural sector. Such issue is partially delivered from Molinos-Senante et al. (2016) where an attempt of highlighting efficiency differences between farmers, with immediate access to water or not is being made, underlying the need for policy framework modifications. In this line of reasoning, other agronomic factors such as access to land with high levels of organic matter, or vulnerability from specific pests should be considered in the evaluation process.

4.3 DEA extensions

DEA has not been combined with any other model or methodology for 30% of the examined references, proving that most researchers are implementing additional steps after the calculation efficiency scores. From the remaining 82 papers, regression models was the most frequent option such Tobit (10), Truncated (4), Ordinary Least Squares (OLS) (4) and other not specified linear regression models (6). Tobit model was used for checking which socio-economic variables are affecting the extracted efficiency scores (Hassen et al. 2017; W Kamal and Ilmas 2017). As mentioned from (Chang et al. 2022) the use of OLS model can be biased due to the

potential inclusion of zero values extracted from the DEA implementation process. Martinsson & Hansson (2021) have used OLS to assess the effect of subsidies in the performance of dairy farms and their overall productivity. Frangu et al. (2018) incorporated in their linear regression model aspects like farmers training on crop nutrition or type of power source used (e.g. electricity, fuel) fulfilling also other dimensions than the typical social characteristics (e.g. age, education, income, years of experience).

Apart from the regression models Malmquist index was used in 10 cases in order to check efficiency differences between years. Pan et al. (2021) used Malmquist index to assess differences of total factor productivity between the years 2015–2018, proving that there was a significant increase in productivity of various Chinese regions. Ren et al. (2017) applied the same index to depict the water use efficiency per year in order to propose regional changes to policymakers. Another least explored index used in combination with the DEA is Theil index, which was used for exploring economic inequalities between different Chinese regions regarding their eco-efficiency (Pang et al. 2016).

LCA is another commonly combined analysis with the DEA for assessing the environmental impacts of agricultural activities. In the examined sample, 14 papers (11%) implemented the afore-mentioned methodology. When LCA is applied there are two approaches of either implementing DEA in the initial stage and then target values are used (Grados et al. 2017), or LCA is performed first and its results are proceeding to further analysis with the DEA (Rybaczewska-Błazejowska and Gierulski 2018). For instance, Mohammadi et al. (2022) have assessed the impacts of agricultural activity to air, water and soil, clarifying the differences between current and target values for Iranian wheat farms.

Principal component Analysis (PCA) and Factor Analysis (FA) were used from a small number of papers (4). After the collection of economic, social and environmental data, Sánchez-Zamora and Gallardo-Cobos (2019) have applied PCA for grouping Spanish regions with common characteristics to measure and compare their resilience scores, extracted from DEA. Ramos de Oliveira et al. (2022) implemented PCA in order to elucidate the interactions among the sustainability factors, proving that social and environmental dimensions should not be neglected when transportation routes of agricultural products are being assessed for their efficiency levels.

Kord et al. (2021) have incorporated a sensitivity analysis in their approach, to assess the allocation of human resources in a 2 stage Network DEA model. More precisely, this paper seeks to address the optimal value of human resources intervention in the plantation/maintenance of the cultivar (first stage) and harvesting (second stage). Abbas et al. (2022) used the aforementioned analysis, so as to indicate the change of crop output under the condition of different number of inputs each time. Grey relational analysis was applied to check the influence of the included variables to the environmental performance of China's families (Y. Yang et al. 2019).

Lastly, special attention was paid to the incorporation of spatial characteristics in the reviewed papers. Tian et al. (2016) have implemented spatial analysis after estimating the efficiency scores for Chinese grape farms. Spatial Durbin

Model was implemented from the following researchers to identify technological spillovers through different regions (J. Li et al. 2021; Wu et al. 2022; P. Xu et al. 2022). Examining the spatial relationship of the acquired results is a necessity for agricultural operational research to reveal potential patterns that may have been neglected in the analysis process.

4.4 Data type

A similar pattern of used inputs Pesticides, Diesel, Electricity, Fertilizers, Labor, Machinery, Seeds, and Yield as used output is revealed through this process. However, it should be underlined that irrigation has been used only from 24 surveys, raising awareness about data collection and data availability of such a valuable natural source. As it was also mentioned in the data analysis section, farm data regarding agronomic characteristics are missing. This situation does not permit researchers to perform a fairer assessment, treating all the involved DMUs as homogenous.

Apart from the quantitative variables, none of the papers used qualitative variables (e.g. Likert scale) when performing DEA, a valuable characteristic for assessing agronomic characteristics which cannot be easily or precisely measured or quantified. Cook (2004) provides the appropriate methodology on how the incorporation of qualitative data can be implemented. Considering time-series data, 34 out of 118 included references have analyzed data of more than one year. Authors selected to include this variable in order to check the validity of acquired results that may present high variations due to external factors. For instance, bad weather conditions can result in small yield for one region, perceiving it as inefficient compared with another one in the same year. Seasonal differences should be carefully considered when DEA is applied in agriculture. It should be also highlighted that only one survey has applied Window DEA to treat time-series data (Gatimbu et al. 2020), which is the most appropriate methodology for this type of data. Moreover, only none of the studies has incorporated any information from GIS system, highlighting the need for acquiring up-to-date data in an easier and more precise way. In this way, farms or regions can be better characterized, setting on the optimisation process all their unique features that may influence the validity of acquired results.

4.5 Data collection and processing

Although there is a detailed record of all the included sources, in this review four larger groups were created. Data were collected through; public databases (EUROSTAT, FADN, FAOSTAT, China Statistical Yearbook, other sources) by 49% (58 papers); personal interviews by 45% (53 papers) funded project collaboration by 3% (3 papers); private sector by 3% (2 papers) and not specified in one of them. It should be mentioned that Seo and Umeda (2021) used data from field experiments, an aspect which was absent from this literature review process and should be further promoted for acquiring accurate results. Total sample size has been added as a variable to check the rule of thumb for the ratio of DMUs involved compared to the

number of examined variables. None of the examined papers appeared to be problematic on that.

Focusing on data collection through personal interviews, a small part of them (12 papers) had a reference on how they collected their samples. More precisely, 4 referred to Random sampling technique formula (Raheli et al. 2017; Ramezani et al. 2022; Sherzod et al. 2018; Sui et al. 2022); another 4 to Cochran technique (Ashraf et al. 2020; Esfahani et al. 2017; Molinos-Senante et al. 2016; Payandeh et al. 2021); 2 to Yamane technique (Haq and Boz 2019; Ul Haq et al. 2020); 1 to Stratified Sampling formula (Godoy-Durán et al. 2017) and one to snowball sampling method (Mwambo et al. 2021).

To authors' surprise, the greatest part of the papers (51%) did not specify which DEA software they used to acquire DEA results, which would be helpful for results reproducibility. DEA Solver, DEAP, and STATA were the most used as shown in Fig. 7. Regarding the RStudio software, Benchmarking library was used in 4 papers while deaR library in another 2.

4.6 Sustainability dimension

Lastly, all papers were grouped by the sustainability dimension that they represent. Although there is a large discussion about how we can define sustainability and which aspects should be included (Purvis et al. 2019), for the scope of this review sustainability is represented by the three aspects of economic development, environmental protection, and social inclusion. It should be mentioned that categorization was made based on two stages. The first stage was referring to the variables inserted immediately in the DEA model, while the second stage was examining the overall contribution to sustainability assessment. For instance, if a paper was using typical inputs and outputs (e.g. labour, fertilizers, land, energy and overall production), it was perceived as solely economic. When a paper has included in the above stated variables an undesirable output (e.g. GHG emissions) or LCA results, it was classified in the economic and environmental category. There were also 2 cases in

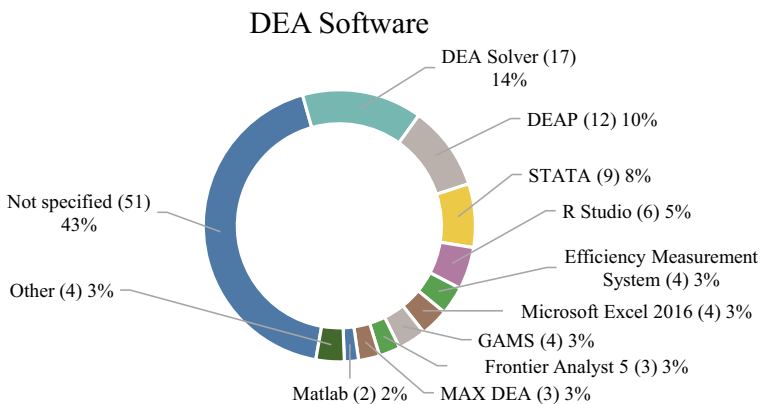


Fig. 7 DEA software

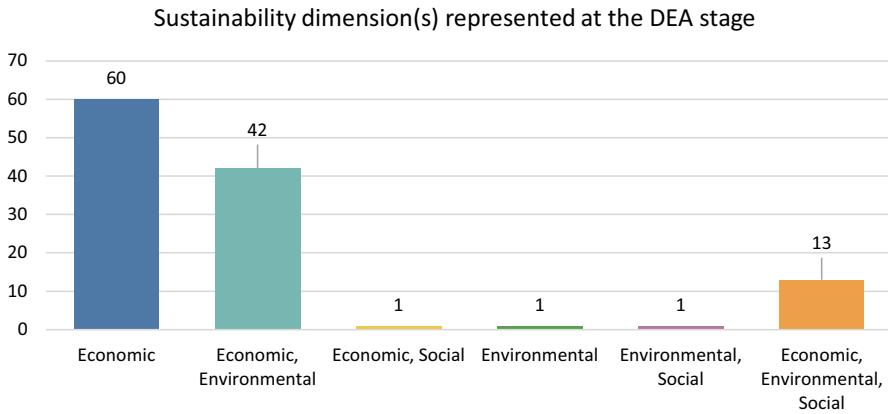


Fig. 8 Sustainability dimension(s) represented at the DEA stage

which Human Development Index (HDI) (Babazadeh et al. 2018; Khanjarpanah et al. 2017) was used in the optimization process, meaning that at the DEA stage the social aspect was represented. As Fig. 8 shows, at the DEA stage half of the papers are contributing only to the economic aspect, 35% concerns both economic and environmental aspect, while only in 11% of the examined papers are representing all sustainability dimensions. For instance, Tang et al. (2022) have incorporated land cost, HDI, annual precipitation and amount of water resources covering all three aspects of sustainability. Sánchez-Zamora & Gallardo-Cobos (2020) have embodied 22 indicators covering economic, environmental, social, institutional and spatial development characteristics.

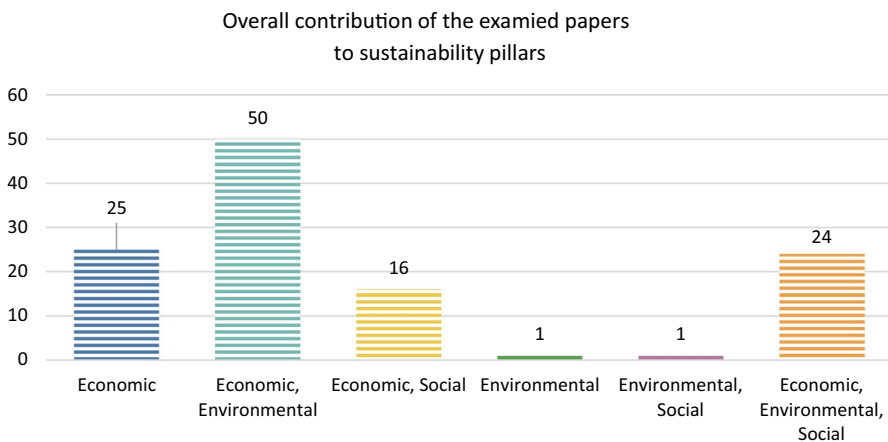


Fig. 9 Overall contribution of examined papers to sustainability pillars

Following the same rationale as at the first stage, the examined papers were categorised by the total combination of variables and methods that they implemented in their approaches of sustainability. Figure 9 shows that there is a shift from solely *economic* perspective of Fig. 8 to a combined *economic and environmental* approach. In other words, in many cases where only economic pillar was represented in a DEA methodological approach, authors embodied methodologies such as LCA (Beltrán-Esteve et al. 2017; Gamboa et al. 2020) or functions for the calculation of CO₂ emissions (Ashraf et al. 2020; Basavalingaiah et al. 2020; Ilahi et al. 2019) or environmental cost benefit analysis (Mwambo et al. 2020). Economic and social aspect increased as well, due to the fact that DEA outcomes were used as dependent variables in regression models such as Tobit (Haq and Boz 2019; Sherzod et al. 2018) or truncated regression (Liu and Sun 2019; Martino et al. 2016), to identify significant relations of socioeconomic variables to them. It is really positive the fact that the number of DEA papers contributing to all sustainability pillars increased from 13 to 24, representing almost 20% of the sample, thus the percentage remains low given the fact that examined papers have been retrieved through a structured search for sustainability in agriculture.

As a final part of this review, obtained results were visualized to provide a clear image to the reader. As expected “sustainability” term is closely related to DEA. LCA term is also present, meaning that authors either refer to the applicability of this method in their papers, or they implement it in combination with

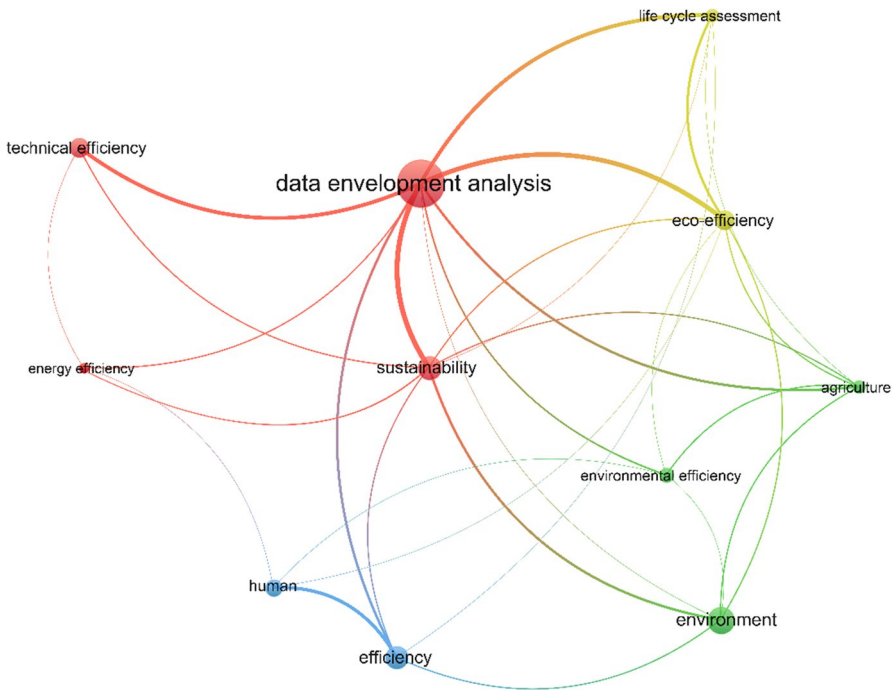


Fig. 10 Keywords’ relationship of the included papers

DEA, a result which was extracted from Sect. 4.3. In the lower left corner of Fig. 10, there is the label “human” which indicates that even if the number of documents including social features remains small, this term is under authors’ consideration.

5 Discussion

The main objective of this study is to identify methodological gaps and propose future directions for the operational research field of agriculture, considering sustainability as a driving force. Additionally, the contribution of the reviewed papers to the fulfillment of the 3 aspects of sustainable development was evaluated. The significance of this literature review does not stem from its findings but from highlighting missing aspects or points that needs to be improved.

Over the years there is a clear approach of constantly finding new methodologies to better integrate the concepts of reduced resource availability and environmental protection in DEA methodology. As Galanopoulos et al. (2006) stated, farmers can only control their inputs and they have less impact on the final output, due to a series of external factors. This is the reason why the input-oriented approach is selected, to minimize the risk of the invested capital from the farmer’s side as well as promote environmental protection through reduced use of agrochemicals. Although fertilizers skyrocketed the production potential on a global scale, high amounts of energy are needed for their production and distribution (Dimitrijević et al. 2020). This is another reason why the input-oriented approach is selected, leading to production systems with lower energy requirements.

Results indicate that the greatest part of surveys was held out on a local level, thus DEA remains a handful tool for measuring the performance on a greater scale. However, none of the examined papers have assessed the infrastructure of agricultural domains for each country. For example, how the funds of EU agricultural sectors are distributed in subsections like crop production, livestock production and mixed systems, through hierarchical network models (Kremantzis et al. 2022). It should be also underlined that the implementation of weights would lead to more reliable results (Mosbah et al. 2020; Thompson et al. 1994, 1995). This is a point of great importance for the agricultural field, where multiple external factors affect the interactions of the used inputs, also influencing the final output. For example, temperature affects nitrogen release rates depending on fertilizer type or soil type (Ransom et al. 2020), soil pH plays an important role in plant growth (Xiao et al. 2017), salinity (Hessini et al. 2019), and a series of factors that affect the final output can be inserted in DEA model as weights. That is the reason why the incorporation of GIS information in DEA methodology is essential, but there is a limited number of papers available online with this combination (Liang et al. 2019).

Estimation of undesirable outputs is another point of interest for agricultural productivity. Literature review shows that most researchers use CO₂ or GHG emissions to align their papers with the global effort for GHG emissions reduction. These outcomes are in accordance with Streimikis and Saraji’s (2021) review results. However, there is an increasing need for creating circular flows to eliminate the wasted energy, supporting this transition by an appropriate policy framework (Guo et al. 2021).

Moreover, it should be stated that data availability remains an issue in the agricultural field. Almost half of the surveys used data acquired through personal interviews, proving that data collection is a time-demanding process that also involves an increased risk of imprecise data. On top of that, researchers have limited access only to basic information as shown in Table 3, mainly because additional data collection requires an establishment of greater infrastructure e.g. agro-related applications where farmers insert either manually or automatically their data, local agro-managers provide a first stage data screening and lastly, researchers provide further insights and results from visualization. Further assessment is needed regarding qualitative data like the quality of sowing, quality of spraying or quality characteristics of the final product. TOPSIS Model, which can handle both scale and categorical data, can be easily combined with DEA methodology in the agricultural sector, embodying a wider range of involved variables in the benchmarking process (Kyrgiakos et al. 2021a, b; Wang et al. 2021).

Additionally, out of the 34 papers that used time-series data, 31 extracted them from public datasets, 1 from project collaboration, and another 1 from the private sector. By this statement a lack of constant monitoring by cultivar type and by specific region is highlighted, as the remaining papers performed an annual analysis, indicating the need for incorporating a greater part of the variability, derived from of multiple years analyses.

The social dimension is the least represented aspect when measuring efficiency in agriculture under the sustainability framework, a conclusion that derives both from the present review, but also has been highlighted in literature reviews of energy and environmental fields (Tsaples & Papathanasiou 2021; Zhou et al. 2018). Moreover, even though the economic dimension is the most highlighted one in Fig. 8, it should be considered that when estimating the potential reduction of the amount of fertilizer per land unit, it is apparent that this act enhances environmental protection. Though the main outcome of this survey, that the social aspect is still underrepresented, as highlighted in Fig. 9.

The limitation of this research lies in the fact that the sources were extracted only by using a firm approach of paper selection, searching for DEA and sustainability and agriculture «terms» on their title, abstract, or keywords. Although authors are aware of the existence of a higher number of papers with DEA implementation in the agricultural sector with great potential, e.g. application of DEA in agriculture at the EU level (Kočíšová 2015; Madau et al. 2017), local level (Işgin et al. 2020), comparisons of DEA results with SFA (Theodoridis and Psychoudakis 2008) or newer approaches like 2-stage DEA (F. Ren et al. 2021), engagement of spatial characteristics (Z. Li et al. 2021), DEA with Artificial Neural Networks (ANNs) (Vlontzos and Pardalos 2017) or Window DEA approaches (Kyrgiakos et al. 2021a, b; Shahraki et al. 2019), thus they were excluded because they did not fulfill the previously stated limitation. Moreover, prominent journals like American Journal of Agricultural Economics or Journal of Agricultural Economics are missing from the two databases, a fact that should be seriously considered by researchers when using these search engines.

Eco-efficiency was another serious consideration when designing this survey due to the fact that there is a considerable effort of several researchers under this term as well (Gómez-Limón et al. 2012; Kiani Mavi et al. 2019; Rebolledo-Leiva et al. 2019). However, using this specific term the pillar of environmental protection would be overestimated and this may lead to non-objective results. Taking the

above-mentioned limitations into consideration, authors agreed to proceed with this approach, assuming that the sample size is representative and can provide a simple and realistic overview to the reader. As a final remark, the “agriculture” term should be placed in title, abstract, or keywords section from the future authors, to easily distinguish their papers from closely related ones.

6 Conclusions

In this literature review, 120 papers were included referring to the use of DEA in the agricultural sector considering sustainability. Results indicate that there is a need for a more systematic data collection that will incorporate data of agricultural practices (both quantitative and categorized), weather data, as well as an effort of combining DEA methodology with information extracted from GIS databases. Also, it is a necessity to perform optimization methods on a multiple-year basis, to engage all the involved variability. Such applications will permit the implementation of more complex DEA models with greater adaptability in real-case scenarios. The integration of weights in DEA models can contribute to achieving the above goal, ensuring the same baseline before the benchmarking process. Additionally, it is necessary to integrate social factors, especially in cases where the aim of the research is to provide information to policymakers. Concluding, data availability and implementation of more complex methodologies are needed to acquire results with greater explanatory power, contributing to the achievement of sustainable development principles in the agricultural sector.

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Data availability The data are available upon request to the corresponding author.

Declarations

Conflict of interest The authors declare no conflict of interest.

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Appendix

See Table 3.

Table 3 All the included references of the reviewed papers

Authors	Ap. Lvl	Inputs	Outputs	Application system
Skevas and Serra (2016)	L	Capital, Labor, Land, Other costs, Pesticides, Fertilizers	Production (Euro)	Arable farms
Pang et al. (2016)	N	Agricultural Machinery, Agricultural film input, Fertilizers	Added Value	Agricultural sector
Tian et al. (2016)	N	Agricultural film input, Agro-chemicals, Diesel, Electricity, Irrigation, Labor, Organic Fertilizers	Production	Grapes
Baležentis et al. (2016)	N	Energy, Labor, Real Fixed Capital Stock	Added Value	Agricultural sector
Mollinos-Senante et al. (2016)	L	Energy, Labor, Pesticides, Fertilizers	Production	Agricultural sector
Ghali et al. (2016)	L	Capital, Intermediate consumption, Labor, Land	Crop output, Livestock output, Other Output	Agricultural sector
C. N. Wang et al. (2016)	L	Equity, Liabilities, total assets	Gross Profit, Net Revenue	Agroforestry
Martino et al. (2016)	L	Capital, Labor, Land, Other costs	Gross Product	Agricultural sector
Vlontzos et al. (2017)	I	Agro-chemicals, Capital, Energy, Labor, Land	Production (Euro)	Agricultural sector
C. Ren et al. (2017)	L	External hidden flow, Import water resources, Local water resources	Local waste output, Local waste system	Agricultural sector
Grados et al. (2017)	P	Agro-chemicals, Labor, Machinery, Seeds, Fertilizers	Production	Potato
Raheli et al. (2017)	L	Agro-chemicals, Diesel, Irrigation, Labor, Machinery, Manure, Seeds, Fertilizers	Yield	Tomato
Godoy-Durán et al. (2017)	L	Economic, Environmental, Social	Yield	Horticulture
Esfahani et al. (2017)	L	Electricity, Land, Manure, Fertilizers	Yield	Corn
Beltrán-Estevé et al. (2017)	L	Income	Ecotoxicity, Eutrophication potential, Global Warming Potential, Human toxicity, Lentil, Ozone	Citrus
Rebolledo-Leiva et al. (2017)	P	Energy, Land, Machinery, Pesticides, Raw materials, Fertilizers	Packaging residues, Production	Blueberry
Lee and Park (2017)	L	Agro-chemicals, Diesel, Electricity, Irrigation, Labor, Machinery, Seed, Fertilizers	Production, straw	Soybeans

Table 3 (continued)

Authors	Ap.	Lvl	Inputs	Outputs	Application system
Y. Wang et al. (2017)	P		Agro-chemicals, Irrigation, Machinery, agricultural population, blue water, green water, irrigated area	Production, Production (Euro)	Agricultural sector
Hassen et al. (2017)	L		Agro-chemicals, Fertilizers, Labor, Land, Machinery, Seeds	Production	Wheat
Martinho (2017)	I		Agro-chemicals, Labor, Labor wages, Fertilizers, total assets	Total Output	Countries
Khanjarpanah et al. (2017)	P		Annual precipitation, Human Development Index, Irrigation, Land, Population, precipitation, temprature, unemployment index	Production	Switchgrass
Kamal and Ilmas (2017)	N		Feed, Labor, Medication, Number of animals, Utilities	Production (Euro)	Broiler
Varela-Candamio et al. (2018)	P		Capital, Labor, Land, Shadow price	Production, Subsidies	Agricultural sector
Rybczewska-Blazejowska & Gierulski (2018)	I		Agricultural Land Occupation, Climate Change, Freshwater Eutrophication, Freshwater ecotoxicity, Human toxicity, Ionizing radiation, Marine Ecotoxicity, Marine Eutrophication, Ozone depletion, Terrestrial acidification, Urban Land Occupation, fossil depletion, metal depletion, natural land transformation, photochemical oxidant formation, terrestrial ecotoxicity, water depletion	Gross output value	Agricultural sector
Sherzod et al. (2018)	L		Labor, Seeds, Fertilizers	Production	Wheat

Table 3 (continued)

Authors	Ap. Lvl	Inputs	Outputs	Application system
He and Zhang (2018)	L	Quality management system, Quality improvement plan, Relative price level per employee, Training time, Equipment Environmental amelioration Cost input rate of research funding	Product qualification rate, Rate of return on total assets, Quick ratio, Profit growth rate-on-time delivery, Rate order completion Rate enterprise reputation, Information level, Strategic objective compatibility, carbon dioxide emission, "three wastes" recycling rate	Agricultural sector
Babazadeh et al. (2018)	N	Annual precipitation, Cost of cultivation, Human Development Index, Land, Number of oil extraction, Population, Sunlight, Water resources	Production	Rapeseed, Soybeans
Dong et al. (2018)	P	Area, Labor, Machinery, Nitrogen	Added Value, CO2 emissions	Agricultural sector
Mutyasira (2018)	L	Farm Sustainability Index	Economic, Environmental, Social variables	Agricultural sector
Izadikhah and Khoshroo (2018)	L	Labor, Machinery, Seed, Fertilizers	Total Production	Maize
Mu et al. (2018)	L	Land, Livestock units, Milk costs, fat content, protein content	Energy use, Gross Margin, Land use, N Surplus, P Surplus	Dairy farms
Frangu et al. (2018)	P	Labor, Land, insecticides	Production	Greenhouse Vegetables
Xing et al. (2018)	N	CO2 Emissions, Energy Usage, Exhaust emission, Hazardous Waste Generation, Waste water discharge, Water withdrawl	Economic output	Multiple Production Sectors
Abbas et al. (2018)	L	Chemicals, Diesel, Electricity, Human labor, Irrigation, Machinery, Seed, Fertilizers	Yield	Wheat
Masuda (2019)	L	Agro-chemicals, Buildings, Electricity, Land, Machinery, Production costs, Seeds, Fertilizers	Yield, Yield (Straw)	Rice
Rodrigues et al. (2019)	P	Economic, Environmental, Social	Production (Euro)	Fisheries
Sintori et al. (2019)	L	Feed, Labor, Land, variable capital cost	Meat, Milk	Sheep Farms

Table 3 (continued)

Authors	Ap. Lvl	Inputs	Outputs	Application system
Dania et al. (2019)	T.M	Economic, Environmental, Social	System Requirements	Agricultural sector (Supply Chain)
Saputri et al. (2019)	L	Capital, Energy, Labor, Material and Services, Services	Production	GMO & non-GMO Products
Tan et al. (2019)	N	Equity financing cost, Interest expenses, Investment in innovation, Main business cost, Total debt	Economic value added, Return on asset ratio, Weighted average return	Agricultural businesses
Liang et al. (2019)	P	Agro-chemicals, Labor, Land, Manure, Material and Service, Seeds, Fertilizers	Gross output value	Greenhouse Vegetables
Bourmaris et al. (2019)	P	Agro-chemicals, Area, Labor, Other costs, Seeds, Fertilizers	Gross Returns	Greenhouse Vegetables
Elhag and Boteva (2019)	L	Agro-chemicals, Diesel, Electricity, Irrigation, Labor, Seeds, Fertilizers	Yield	Greenhouse Vegetables
Grados and Schrevens (2019)	L	Labor, Machiner, Fertilizers, Pesticides, Fungicides	Production	Potato
Sánchez-Zamora and Gallardo-Cobos (2019)	P	Economic, Environmental, Social	Composite indicator	Agricultural sector
Ilahi et al. (2019)	P	Chemicals, Diesel, Electricity, Labor, Machinery, Seeds, Water, Fertilizers	Yield (Wheat grain)	Wheat
Ozden and Ozer (2019)	N	Capital, Labor, Land, Pesticides, Population, cattle stock, Fertilizers	Production (Euro)	Agricultural sector
Haq and Boz (2019)	L	Labor, Fertilizers	Production	Tea
Y. Yang et al. (2019)	L	2 models, Fertilizers, Fertilizer per Ha, Labor, Land, Machinery, Pesticide per Ha, Pesticides, Seeds	Crop output	Crop Farms
Liu and Sun (2019)	L	Land, Other costs, Fertilizers	Bamboo roots, Bamboo wood, Production, Production (Euro)	Timber
Watto and Mugerá (2019)	L	Agro-chemicals, Farm size, Irrigation, Labor, Seed, Fertilizers	Yield	Wheat

Table 3 (continued)

Authors	Ap. Lvl	Inputs	Outputs	Application system
Gatimbu et al. (2020)	L	Capital, Energy, Labor, Land, Material and Service	Only undesirable outputs	Tea
Gamboa et al. (2020)	L	Labor, Machinery, Pesticides, Fertilizers	Production	Quinoa
Coluccia et al. (2020)	N	Gross Capital, Irrigation, Labor, Land, Fertilizers	Production	Agricultural sector
(Ul Haq et al. 2020)	L	Labor, Fertilizers	Production	Tea
Pereira Domingues Martinho (2020)	I	Energy costs, Fixed assets, Labor	Total Output	Agricultural sector
Mwambo et al. (2020)	L	Agricultural Services, Evapotranspiration, Human labor, Seeds, animal Labor, Fertilizers, topsoil loss	Yield	Wheat
Ayoubu and Vigeant (2020)	L	Capital, Labor, Land, Pesticides, Raw materials	Production	Wheat
Bartova and Fandel (2020)	L	Energy, Fixed assets, Labor, Land	Production	Wheat
Ashraf et al. (2020)	L	Agro-chemicals, Diesel, Electricity, Irrigation, Labor, Machinery, Seed	Yield (Cereals), Yield (Straw)	Wheat
Basavalingaiah et al. (2020)	L	Agro-chemicals, Diesel, Energy, Farmyard manure, Irrigation, Labor, Machinery, Seeds, Fertilizers	Grain Yield, Yield (Straw)	Rice
Nguyen et al. (2020)	L	Crop production cost, Labor, Land, Other costs, Pesticides	Production	Orange
García-Cornejo et al. (2020)	L	Depreciation expenses, Labor, fixed capital cost, variable capital cost	Production (Euro)	Dairy farms
Nguyen et al. (2020)	N	Land, Family labor, Outsourced labor cost, Crop Production cost, Other expenditures	Production	Oranges
Grassauer et al. (2021)	N	Aquatic ecotoxicity, Cumulative energy demand, Global warming potential, Normalized eutrophication	FNI, HINVf, net food production-protein	Agricultural sector

Table 3 (continued)

Authors	Ap. Lvl	Inputs	Outputs	Application system
Lucas et al. (2021)	I	Acidification, Eutrophication, Fresh water withdrawals, GHG emissions, Land Use	Calories, Qualifying index	food sector
Domagala (2021)	I	Energy, Labor, Land, Fertilizers	Production, net value added	Agricultural sector
Papadopoulou et al. (2021)	L	Labor, Number of animals, fixed capital cost, variable capital cost	Net income	Small ruminant farms
Kord et al. (2021)	P	Area, Irrigation, Labor	Production, Production (Euro)	Agricultural sector
Khoshroo et al. (2021)	N	Biocides, Electricity, Energy, Machinery, Fertilizers	Production (Euro)	Tomato
G. Singh et al. (2021)	L	Agro-chemicals, Biocides, Electricity, Fuel, Irrigation, Labor, Machinery, Seeds	Grain Yield	Wheat
Cecchini et al. (2021)	L	Area, Feed, Labor, Livestock units	Meat, wool	Sheep Farms
Debbarma et al. (2021)	L	Capital, Energy, Labor	Production (Euro)	Agricultural sector
P. Singh, Singh, Sodhi, and Benbi (2021)	L	Biocides, Energy, Machinery, Seed, Fertilizers	Production, Production (Euro)	Rice, Wheat, rotation
M. Zhang et al. (2021)	I	Fertilizers, Irrigation, Land, Machinery	Agricultural Output, CO ₂ emissions	Agricultural sector
Streimikis et al. (2021)	I	Energy consumption, Labor, Land, fixed consumption	Purchasing Power Parity	Agricultural sector
Payandeh et al. (2021)	L	Agro-chemicals, Diesel fuel, Human labor, Machinery, Oil, Seeds, Fertilizers	Grain Yield, Yield (Straw)	barley
Güney (2021)	L	Fuel, Labor, Machinery, Pesticides, Seed, Fertilizers	Production	Wheat
Kyrgiakos et al. (2021a)	L	Energy, Irrigation, Labor, Land, PNPs, Seeds	Production, Production (Euro), Social characteristics	Cotton
Basavalingaiah et al. (2022)	L	Agro-chemicals, Diesel, Fertilizers, Labor, Lime, Machinery, Manure	Coffee, Yield	Coffee
Pan et al. (2021)	N	Energy, Land, Technology, funds, resources	Production	Agricultural sector

Table 3 (continued)

Authors	Ap. Lvl	Inputs	Outputs	Application system
Lamkowsky et al. (2021)	L	Capital, Feed, Labor, Land, Machinery, Number of animals, Pesticides, Seeds, Veterinary costs, Fertilizers	Dairy Sales, Other Sales	Dairy farms
P. Singh, Singh, Sodhi, and Sharma (2021)	L	Biocides, Diesel, Electricity, Fuel, Irrigation, Labor, Seed, Fertilizers	Production	Wheat
Banaś et al. (2021)	L	Area, Labor, Land, Logging costs, Other costs, Protection costs, Silviculture, Standing volume	Production	Timber
Martinsson and Hansson (2021)	N	Energy expenditures	Contribution to global warming	Dairy farms
Y. Zhang et al. (2021)	I	CO ₂ Emissions, Land, Yield, food losses, protein supply	Agricultural added value, import dependency ratio, irrigated area	Agricultural sector
Nirmal Ravi Kumar and Babu (2021)	L	Manure, Seeds, gypsum	Production	Groundnut
Mwambo et al. (2021)	L	Agricultural Services, Evapotranspiration, Human labor, Seeds, animal Labor, Fertilizers, topsoil loss	Yield	Maize
J. Li et al. (2021)	N	Labor, Land, Machinery, Fertilizers	Agricultural added value	Agricultural sector
Bagheri (2021)	I	Electricity, Labor	CO ₂ emissions, GDP	Agricultural sector
Seo and Umeda (2021)	L	Pest control cost	Gross farm income, Surplus of working hours	Rice
Tang et al. (2022)	N	Irrigation, Labor, Land, Machinery, Pesticides, Plastic film, Fertilizers	Economic output, Environmental output, Social output	Agricultural sector
P. Xu et al. (2022)	N	Agro-chemicals, Area, Electricity, Irrigation, Labor, Machinery	Output value	Agricultural sector
Guth et al. (2022)	N	Capital, Labor, Land	Production	Agricultural sector
Bernard et al. (2022)	I	Capital, Labor, Land	Agricultural added value	Agricultural sector

Table 3 (continued)

Authors	Ap.	Lvl	Inputs	Outputs	Application system
Ramos de Oliveira et al. (2022)	N		Diesel, Fleet condition, Fuel consumption, Gini index, Production costs, Warehouse capacity, photochemical oxidant formation, transportation matrix	GHG emissions, Wheat, logistic cost	Logistics
Streimikis et al. (2022)	I		Capital, Energy, Labor, Land	Net income	Agricultural sector
S. Wang et al. (2022)	P		Labor, Land, Blue Footprint, Green Footprint	Yield	Agricultural sector
Sharma (2022)	I		Land, Seeds, Fertilizers	Production	Rice
Yan et al. (2022)	L		Agro-chemicals, Irrigation, Labor, Land, Machinery	Production	Grain
Kord et al. (2022)	N		Irrigation, Labor, Land	Net income, Yield	Agricultural sector
Ziętek-Kwaśniewska et al. (2022)	P		Depreciation expenses, Electricity, Labor, Other costs, Raw materials	Net sales revenue	Dairy farms
Chaubey et al. (2022)	P		Area, GDP, Labor, Population, per capita-tion	Production	Agricultural sector
W. Li et al. (2022)	N		Capital, Labor, Land	Net income	Agricultural farms
Gao et al. (2022)	N		Family Labor, Hired Labor, Irrigation, Machinery, Manure, Pesticides, Seeds, Fertilizers	Yield	Rice
Chang et al. (2022)	N		Hired Labor, Irrigation, Machinery, Pesticides, Seed, Seeds, Fertilizers	Production	Agricultural sector
Ramezani et al. (2022)	L		Agro-chemicals, Irrigation, Labor, Land, Manure, Nitrogen balance	Yield	Saffron
Mohammadi et al. (2022)	L		Agro-chemicals, Biosides, Diesel, Electricity, Irrigation, Labor, Machinery, Seeds, Urea	Yield	Wheat

Table 3 (continued)

Authors	Ap. Lvl	Inputs	Outputs	Application system
Abbas et al. (2022)	L	Biocides, Diesel, Irrigation, Labor, Machinery, Manure, Pesticide risk, Pesticides, Phosphorus balance, Seed, Fertilizers	Yield	Cotton
Turner et al. (2022)	L	Feed, pullets	Eggs	egg farms
L. Yang et al. (2022)	P	Diesel, Fertilizers, Pesticides	Income, Yield	Sugarcane
Khan and Ali (2022)	N	Land	Yield	Clover
Nyamuhirwa et al. (2022)	L	Capital, Labor	Added Value	Agricultural sector
Sui et al. (2022)	P	Capital, Labor, Land	Yield	Garlic
Wu et al. (2022)	N	Agricultural firm input, Expected output, Irrigation, Labor, Land, Machinery, Pesticides, Fertilizers	Carbon emissions, Net income, Non point sources, Output value	Agricultural sector
Nodin et al. (2022)	P	Agro-chemicals, Capital, Labor, Land	Yield	Rice
Dania et al. (2022)	L	Collabotation Factors	Economic, Environmental, Social	Agricultural sector
Lu et al. (2022)	N	(3 Stage NDEA model with circular flows)		Agricultural sector

* Applicability level: Local (L), Province (P), National (N), International (I), Theoretical Model (T.M).

** Output section does not include undesirable outputs.

References

- Abbas A, Zhao C, Waseem M, Ahmed Khan Ahmad KR (2022) Analysis of energy input-output of farms and assessment of greenhouse gas emissions: a case study of cotton growers. *Front Environ Sci*. <https://doi.org/10.3389/fenvs.2021.826838>
- Abbas A, Iqbal T, Ahmad M, Yousaf K (2018) Implementation of a novel approach for the evaluation of energy efficiency, management needs and sustainability of wheat production Work of PhD desertation View project Image Processing View project. <https://www.researchgate.net/publication/328448720>
- Aigner D, Lovell CAK, Schmidt P (1977) Formulation and estimation of stochastic frontier production function models. *J Economet*. [https://doi.org/10.1016/0304-4076\(77\)90052-5](https://doi.org/10.1016/0304-4076(77)90052-5)
- Ashraf MN, Mahmood MH, Sultan M, Banaeian N, Usman M, Ibrahim SM, Butt MUBU, Waseem M, Ali I, Shakoor A, Khan ZM (2020) Investigation of input and output energy for wheat production: a comprehensive study for Tehsil Mailsi (Pakistan). *Sustain (Switzerland)*. <https://doi.org/10.3390/SU12176884>
- Ayoub K, Vigeant S (2020) Can we really use prices to control pesticide use? Results from a nonparametric model. *Environ Model Assess*. <https://doi.org/10.1007/s10666-020-09714-w/Published>
- Babazadeh R, Yavarirad MV, Bashusqeh EM (2018) Location optimization of rapeseed and soybean cultivation areas considering economic, climatic and social criteria. *Int JSoc Ecol Sustain Develop* 9(3):53–65. <https://doi.org/10.4018/IJSESD.2018070104>
- Bagheri N (2021) Evaluation of the efficiency of UAE sectors on the basis of sustainable development objectives and circular economy using DEA. *Int Conf Cyber Manag Eng, CyMaEn*. <https://doi.org/10.1109/CyMaEn50288.2021.9497270>
- Baležentis T, Li T, Streimikiene D, Baležentis A (2016) Is the Lithuanian economy approaching the goals of sustainable energy and climate change mitigation? Evidence from DEA-based environmental performance index. *J Clean Prod* 116:23–31. <https://doi.org/10.1016/j.jclepro.2015.12.088>
- Banaś J, Utnik-Banaś K, Zięba S, Janeczko K (2021) Assessing the technical efficiency of timber production during the transition from a production-oriented management model to a multifunctional one: a case from Poland 1990–2019. *Forests* 12(9):1287. <https://doi.org/10.3390/f12091287>
- Bartova L, Fandel P (2020) Membership in agricultural producer organizations and farm technical efficiency in Slovakia. *Equilibrium* 15(3):489–509
- Basavalingaiah K, Paramesh V, Parajuli R, Girisha HC, Shivaprasad M, Vidyashree G, v Thoma Hanumanthappa Yogesh Misra Bhat Irfan Rajanna GMGSSDSMMGA (2022) Energy flow and life cycle impact assessment of coffee-pepper production systems: an evaluation of conventional, integrated and organic farms in India. *Environ Impact Assess Rev*. <https://doi.org/10.1016/j.ear.2021.106687>
- Basavalingaiah K, Ramesha YM, Paramesh V, Rajanna GA, Lal Jat S, Misra SD, Gaddi AK, Girisha HC, Yogesh GS, Raveesha S, Roopa TK, Shashidhar KS, Kumar B, El-Ansary DO, Elansary HO (2020) Energy budgeting, data envelopment analysis and greenhouse gas emission from rice production system: a case study from puddled transplanted rice and direct-seeded rice system of Karnataka. *India Sustain (Switzerland)*. <https://doi.org/10.3390/SU12166439>
- Beltrán-Esteve M, Reig-Martínez E, Estruch-Guitart V (2017) Assessing eco-efficiency: a meta-frontier directional distance function approach using life cycle analysis. *Environ Impact Assess Rev* 63:116–127. <https://doi.org/10.1016/j.ear.2017.01.001>
- Bernard BM, Song Y, Hena S, Ahmad F, Wang X (2022) Assessing Africa's agricultural TFP for food security and effects on human development: evidence from 35 Countries. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su14116411>
- Bogetoft P, Otto L (2011) *Benchmarking with DEA, SFA, and R (Vol. 157)*. Springer New York. Doi: <https://doi.org/10.1007/978-1-4419-7961-2>
- Bournaris T, Vlontzos G, Moulgianni C (2019) Efficiency of vegetables produced in Glasshouses: the impact of data envelopment analysis (DEA) in land management decision making. *Land*. <https://doi.org/10.3390/land8010017>
- Calicioglu O, Flammini A, Bracco S, Bellù L, Sims R (2019) The future challenges of food and agriculture: an integrated analysis of trends and solutions. *Sustainability* 11(1):222. <https://doi.org/10.3390/SU11010222>
- Cecchini L, Vieceli L, D'Urso A, Magistrali CF, Forte C, Mignacca SA, Trabalza-Marinucci M, Chiorri M (2021) Farm efficiency related to animal welfare performance and management of sheep farms

- in marginal areas of Central Italy: a two-stage DEA model. *Ital J Anim Sci* 20(1):955–969. <https://doi.org/10.1080/1828051X.2021.1913076>
- Chang M, Liu J, Shi H, Guo T (2022) The effect of off-farm employment on agricultural production efficiency: micro evidence in China. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su14063385>
- Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision making units. *Eur J Oper Res* 2(6):429–444. [https://doi.org/10.1016/0377-2217\(78\)90138-8](https://doi.org/10.1016/0377-2217(78)90138-8)
- Chaubey V, Sharanappa DS, Mohanta KK, Mishra VN, Mishra LN (2022) Efficiency and productivity analysis of the indian agriculture sector based on the Malmquist-DEA technique. *Univ J Agricultural Res* 10(4):331–343
- Coluccia B, Valente D, Fusco G, de Leo F, Porrini D (2020) Assessing agricultural eco-efficiency in Italian Regions. *Ecol Indic*. <https://doi.org/10.1016/j.ecolind.2020.106483>
- Cook WD (2004) Qualitative Data in Dea. In *Handbook on Data Envelopment Analysis* (pp. 153–175). Kluwer Academic Publishers. https://doi.org/10.1007/1-4020-7798-X_6
- Dania WAP, Xing K, Amer Y (2019) Collaboration quality assessment for sustainable supply chains: benchmarking. *Benchmarking An Int J* 26(5):1469–1498. <https://doi.org/10.1108/BIJ-03-2018-0070>
- Dania WAP, Xing K, Amer Y (2022) The assessment of collaboration quality: a case of sugar supply chain in Indonesia. *Int J Product Perform Manag* 71(2):504–539. <https://doi.org/10.1108/IJPPM-11-2019-0527>
- Debbarma J, Lee H, Choi Y (2021) Sustainable feasibility of the environmental-friendly policies on agriculture and its related sectors in India. *Sustainability* 13(12):6680. <https://doi.org/10.3390/su13126680>
- Dimitrijević A, Gavrilović M, Ivanović S, Mileusnić Z, Miodragović R, Todorović S (2020) Energy use and economic analysis of fertilizer use in wheat and sugar beet production in Serbia. *Energies* 13(9):2361. <https://doi.org/10.3390/EN13092361>
- Domagala J (2021) Economic and environmental aspects of agriculture in the eu countries. *Energies*. <https://doi.org/10.3390/en14227826>
- Dong G, Wang Z, Mao X (2018) Production efficiency and GHG emissions reduction potential evaluation in the crop production system based on emery synthesis and nonseparable undesirable output DEA: a case study in Zhejiang Province China. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0206680>
- Elhag M, Boteva S (2019) Conceptual assessment of energy input-output analysis and data envelopment analysis of greenhouse crops in Crete Island. *Greece Environ Sci Pollut Res* 26(35):35377–35386. <https://doi.org/10.1007/s11356-019-05544-w>
- Esfahani SMJ, Naderi Mahdei K, Saadi H, Dourandish A (2017) Efficiency and sustainability of silage corn production by data envelopment analysis and multi-functional ecological footprint: evidence from Sarayan County, Iran. In *J. Agr. Sci. Tech* (Vol. 19)
- European Commission. (2015). Political agreement on new Common Agricultural Policy: fairer, greener, more flexible. https://ec.europa.eu/commission/presscorner/detail/en/IP_21_2711
- Farrell MJ (1957) The measurement of productive efficiency. *J Royal Statistical Soc Series A General* 120(3):253
- Frangu B, Popp JS, Thomsen M, Musliu A (2018) Evaluating greenhouse tomato and pepper input efficiency use in Kosovo. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su10082768>
- Färe R, Grosskopf S, Whittaker G (2007) Network DEA. In *Modeling Data Irregularities and Structural Complexities in Data Envelopment Analysis* (pp. 209–240). Springer US. https://doi.org/10.1007/978-0-387-71607-7_12
- Galanopoulos K, Aggelopoulos S, Kamenidou I, Mattas K (2006) Assessing the effects of managerial and production practices on the efficiency of commercial pig farming. *Agric Syst* 88(2–3):125–141. <https://doi.org/10.1016/j.agsy.2005.03.002>
- Gamboa C, Bojacá CR, Schrevens E, Maertens M (2020) Sustainability of smallholder quinoa production in the Peruvian Andes. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2020.121657>
- Gao L, Gao Q, Lorenc M (2022) Comparison of total factor productivity of rice in China and Japan. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su14127407>
- García-Cornejo B, Pérez-Méndez JA, Roibás D, Wall A (2020) Efficiency and sustainability in farm diversification initiatives in northern Spain. *Sustainability (Switzerland)*. <https://doi.org/10.3390/SU12103983>

- Gatimbu KK, Ogada MJ, Budambula NLM (2020) Environmental efficiency of small-scale tea processors in Kenya: an inverse data envelopment analysis (DEA) approach. *Environ Dev Sustain* 22(4):3333–3345. <https://doi.org/10.1007/s10668-019-00348-x>
- Gerdessen JC, Pascucci S (2013) Data envelopment analysis of sustainability indicators of European agricultural systems at regional level. *Agric Syst* 118:78–90. <https://doi.org/10.1016/j.agry.2013.03.004>
- Ghali M, Latruffe L, Daniel K (2016) Efficient use of energy resources on French farms: an analysis through technical efficiency. *Energies*. <https://doi.org/10.3390/en9080601>
- Godoy-Durán Á, Galdeano- Gómez E, Pérez-Mesa JC, Piedra-Muñoz L (2017) Assessing eco-efficiency and the determinants of horticultural family-farming in southeast Spain. *J Environ Manage* 204:594–604. <https://doi.org/10.1016/j.jenvman.2017.09.037>
- Google Trends. (2021) Sustainability term. https://trends.google.com/trends/explore?q=%2Fg%2F11g6z_llzc&date=today 5-y
- Grados D, Heuts R, Veters E, Schrevens E (2017) A model-based comprehensive analysis of technical sustainability of potato production systems in the Mantaro Valley, Central Highlands, Peru. *Acta Horticulturae* 1154:155–162
- Grados D, Schrevens E (2019) Multidimensional analysis of environmental impacts from potato agricultural production in the Peruvian Central Andes. *Sci Total Environ* 663:927–934. <https://doi.org/10.1016/j.scitotenv.2019.01.414>
- Grassauer F, Herndl M, Nemecek T, Guggenberger T, Fritz C, Steinwider A, Zollitsch W (2021) Eco-efficiency of farms considering multiple functions of agriculture: concept and results from Austrian farms. *J Clean Prod* 297:126662. <https://doi.org/10.1016/j.jclepro.2021b.126662>
- Guo X, Lung P, Sui J, Zhang R, Wang C (2021) Agricultural support policies and China's cyclical evolutionary path of agricultural economic growth. *Sustainability* 13(11):6134. <https://doi.org/10.3390/su13116134>
- Guth M, Stepień S, Smędzik-Ambroży K, Matuszczak A (2022) Is small beautiful? Technical efficiency and environmental sustainability of small-scale family farms under the conditions of agricultural policy support. *J Rural Stud* 89:235–247. <https://doi.org/10.1016/j.jrurstud.2021.11.026>
- Gómez-Limón JA, Picazo-Tadeo AJ, Reig-Martínez E (2012) Eco-efficiency assessment of olive farms in Andalusia. *Land Use Policy* 29(2):395–406. <https://doi.org/10.1016/j.landusepol.2011.08.004>
- Güney O (2021) Eco-efficiency in farm management for sustainable agriculture: a two-stage data envelopment analysis in wheat production. *Polish J Environ Stud* 30(6):5549–5557
- Halkos G, Petrou KN (2019) Treating undesirable outputs in DEA: a critical review. *Econom Anal Policy* 62:97–104. <https://doi.org/10.1016/j.eap.2019.01.005>
- Haq SU, Boz I (2019) Estimating the efficiency level of different tea farming systems in Rize province Turkey. *Ciencia Rural*. <https://doi.org/10.1590/0103-8478cr20181052>
- Hassen A, Marwa BB, Hanan A, Amira M (2017) Analysis of the technical efficiency, pure and scale efficiency of rainfed cereal farms Case of the upper semi-arid. *J Exp Biol Agricultural Sci* <https://doi.org/10.18006/2017.5.S116.S125>
- Hatami-Marbini A, Emrouznejad A, Tavana M (2011) A taxonomy and review of the fuzzy data envelopment analysis literature: two decades in the making. *Eur J Oper Res* 214(3):457–472. <https://doi.org/10.1016/J.EJOR.2011.02.001>
- He X, Zhang J (2018) Supplier selection study under the respective of Low-Carbon supply chain: a hybrid evaluation model based on FA-DEA-AHP. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su10020564>
- Hessini K, Issaoui K, Ferchichi S, Saif T, Abdelly C, Siddique KHM, Cruz C (2019) Interactive effects of salinity and nitrogen forms on plant growth, photosynthesis and osmotic adjustment in maize. *Plant Physiol Biochem* 139:171–178. <https://doi.org/10.1016/j.plaphy.2019.03.005>
- Houshyar E, Azadi H, Almassi M, Sheikh Davoodi MJ, Witlox F (2012) Sustainable and efficient energy consumption of corn production in Southwest Iran: combination of multi-fuzzy and DEA modeling. *Energy* 44(1):672–681. <https://doi.org/10.1016/J.ENERGY.2012.05.025>
- Ilahi S, Wu Y, Raza MAA, Wei W, Imran M, Bayasgalankhuu L (2019) Optimization approach for improving energy efficiency and evaluation of greenhouse gas emission of wheat crop using Data Envelopment Analysis. *Sustainability (Switzerland)*. <https://doi.org/10.3390/SU11123409>
- Izadikhah M, Khoshroo A (2018) Energy management in crop production using a novel fuzzy data envelopment analysis model. *RAIRO – Operat Res* 52(2):595–617. <https://doi.org/10.1051/ro/2017082>

- Işgın T, Özel R, Bilgiç A, Florkowski WJ, Sevinç MR (2020) DEA performance measurements in cotton production of Harran plain, Turkey: a single and double bootstrap truncated regression approaches. *Agriculture* (Switzerland). <https://doi.org/10.3390/agriculture10040108>
- Kamal HAW, Ilmas AM (2017) Robust efficiency and output elasticity of broiler production in Peninsular Malaysia. In *J Agr Sci Tech* (Vol 19)
- Khan WA, Ali H (2022) Topological optimum approach for improving indicators for agricultural sustainability. *J Chem*. <https://doi.org/10.1155/2022/3057504>
- Khanjarpanah H, Pishvae MS, Seyedhosseini SM (2017) A risk averse cross-efficiency data envelopment analysis model for sustainable switchgrass cultivation location optimization. *Ind Crops Prod* 109:514–522. <https://doi.org/10.1016/j.indcrop.2017.09.005>
- Khoshroo A, Izadikhah M, Emrouznejad A (2021) Energy efficiency and congestion considering data envelopment analysis and bounded adjusted measure: a case of tomato production. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2021.129639>
- Kiani Mavi R, Saen RF, Goh M (2019) Joint analysis of eco-efficiency and eco-innovation with common weights in two-stage network DEA: a big data approach. *Technol Forecast Soc Chang* 144:553–562. <https://doi.org/10.1016/j.techfore.2018.01.035>
- Kord A, Payan A, Saati S (2021) Sustainability and optimal allocation of human resource of agricultural practices in Sistan and Baluchestan Province based on network DEA. *J Math Extension* 15(3):1–44
- Kord A, Payan A, Saati S (2022) Network DEA Models with stochastic data to assess the sustainability performance of agricultural practices: an application for Sistan and Baluchestan Province in Iran. *J Math*. <https://doi.org/10.1155/2022/1119630>
- Kočišová K (2015) Application of the DEA on the measurement of efficiency in the EU countries. *Agricultural Econom (Zemědělská Ekonomika)* 61:51–62
- Kremantzis MD, Beullens P, Kyrgiakos LS, Klein J (2022) Measurement and evaluation of multi-function parallel network hierarchical DEA systems. *Socio-Econom Plan Sci*. <https://doi.org/10.1016/j.seps.2022.101428>
- Kumar NR, Babu SC (2021) Can a weather-based crop insurance scheme increase the technical efficiency of smallholders? A case study of groundnut Farmers in India. *Sustainability* (Switzerland). <https://doi.org/10.3390/su13169327>
- Kyrgiakos LS, Pardalos PM, Vlontzos G (2021a) Assessing efficiency of cotton farms considering qualitative factors under DEA TOPSIS model. *Int J Sustain Agricultural Manag Inform* 1(1):1. <https://doi.org/10.1504/IJSAMI.2021.10043510>
- Kyrgiakos LS, Vlontzos G, Pardalos PM (2021b) Ranking EU agricultural sectors under the Prism of alternative Widths on window DEA. *Energies* 14(4):1021. <https://doi.org/10.3390/en14041021>
- Lamkowsky M, Oenema O, Meuwissen MPM, Ang F (2021) Closing productivity gaps among Dutch dairy farms can boost profit and reduce nitrogen pollution. *Environ Res Lett* 16(12):124003
- Lampe HW, Hilgers D (2015) Trajectories of efficiency measurement: a bibliometric analysis of DEA and SFA. In: *European Journal of Operational Research* (Vol. 240, Issue 1, pp. 1–21). Elsevier. <https://doi.org/10.1016/j.ejor.2014.04.041>
- Lee P, Park YJ (2017) Eco-efficiency evaluation considering environmental stringency. *Sustainability* (Switzerland). <https://doi.org/10.3390/su9040661>
- Li J, Chen J, Liu H (2021) Sustainable agricultural total factor productivity and its spatial relationship with urbanization in China. *Sustainability* (Switzerland). <https://doi.org/10.3390/su13126773>
- Li Z, Sarwar S, Jin T (2021) Spatiotemporal evolution and improvement potential of agricultural eco-efficiency in Jiangsu Province. *Front Energy Res* 9:1–12. <https://doi.org/10.3389/fenrg.2021.746405>
- Li W, Wang L, Wan Q, You W, Zhang S (2022) A Configurational analysis of family farm management efficiency: evidence from China. *Sustainability* (Switzerland). <https://doi.org/10.3390/su14106015>
- Liang Y, Jing X, Wang Y, Shi Y, Ruan J (2019) Evaluating production process efficiency of provincial greenhouse vegetables in China using data envelopment analysis: a green and sustainable perspective. *Processes*. <https://doi.org/10.3390/pr7110780>
- Liu L, Sun H (2019) The impact of collective forestland tenure reform on the forest economic efficiency of farmers in Zhejiang province. *Sustainability* (Switzerland). <https://doi.org/10.3390/su11082272>
- Lu LC, Chiu SY, ho Y, Chang TH (2022) Three-stage circular efficiency evaluation of agricultural food production, food consumption, and food waste recycling in EU countries. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2022.130870>
- Lucas E, Galán-Martin A, Pozo C, Guo M, Guillén-Gosálbez G (2021) Global environmental and nutritional assessment of national food supply patterns: Insights from a data envelopment analysis approach. *Sci Total Environ*. <https://doi.org/10.1016/j.scitotenv.2020.142826>

- Madau FA, Furesi R, Pulina P (2017) Technical efficiency and total factor productivity changes in European dairy farm sectors. *Agricultural and Food Econom* 5(1):1–14. <https://doi.org/10.1186/s40100-017-0085-x>
- Mardani A, Streimikiene D, Balezentis T, Saman M, Nor K, Khoshnava S (2018) Data envelopment analysis in energy and environmental economics: an overview of the state-of-the-art and recent development trends. *Energies* 11(8):2002. <https://doi.org/10.3390/en11082002>
- Mardani A, Zavadskas EK, Streimikiene D, Jusoh A, Khoshnoudi M (2017) A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency. *Renew Sustain Energy Rev* 70:1298–1322. <https://doi.org/10.1016/j.rser.2016.12.030>
- Martinho VJPD (2017) Efficiency, total factor productivity and returns to scale in a sustainable perspective: An analysis in the European Union at farm and regional level. *Land Use Policy* 68:232–245. <https://doi.org/10.1016/j.landusepol.2017.07.040>
- Martino G, Polinori P, Tei F, Benincasa P, Turchetti L (2016) An economic analysis of the efficiency and sustainability of fertilization programs at level of operational systems of soft wheat in Umbria. *Agriculture and Agricultural Sci Procedia* 8:298–306. <https://doi.org/10.1016/j.aaspro.2016.02.024>
- Martinsson E, Hansson H (2021) Adjusting eco-efficiency to greenhouse gas emissions targets at farm level – The case of Swedish dairy farms. *J Environ Manag*. <https://doi.org/10.1016/j.jenvman.2021.112313>
- Masuda K (2019) Eco-efficiency assessment of intensive rice production in Japan: Joint application of life cycle assessment and data envelopment analysis. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su11195368>
- Mohammadi A, Venkatesh G, Eskandari S, Rafiee S (2022) Eco-efficiency analysis to improve environmental performance of wheat production. *Agriculture* 12(7):1031. <https://doi.org/10.3390/agriculture12071031>
- Molinos-Senante M, Donoso G, Sala-Garrido R (2016) Are participants in markets for water rights more efficient in the use of water than non-participants? A case study for Limarí Valley (Chile). *Environ Sci Pollut Res* 23(11):10665–10678. <https://doi.org/10.1007/s11356-016-6187-2>
- Mosbah E, Zaibet L, Dharmapala PS (2020) A new methodology to measure efficiencies of inputs (outputs) of decision making units in data envelopment analysis with application to agriculture. *Soc-Econom Plan Sci* 72:100857
- Mu W, Kanellopoulos A, van Middelaar CE, Stilmant D, Bloemhof JM (2018) Assessing the impact of uncertainty on benchmarking the eco-efficiency of dairy farming using fuzzy data envelopment analysis. *J Clean Prod* 189:709–717. <https://doi.org/10.1016/j.jclepro.2018.04.091>
- Mwambo FM, Fürst C, Martius C, Jimenez-Martinez M, Nyarko BK, Borgemeister C (2021) Combined application of the EM-DEA and EX-ACT approaches for integrated assessment of resource use efficiency, sustainability and carbon footprint of smallholder maize production practices in sub-Saharan Africa. *J Clean Prod* 302:126132
- Mwambo FM, Fürst C, Nyarko BK, Borgemeister C, Martius C (2020) Maize production and environmental costs: Resource evaluation and strategic land use planning for food security in northern Ghana by means of coupled energy and data envelopment analysis. *Land Use Policy* 95:104490. <https://doi.org/10.1016/j.landusepol.2020.104490>
- Nguyen TTT, Le HH, Ho TMH, Dogot T, Burny P, Bui TN, Lebailly P (2020) Efficiency analysis of the progress of orange farms in Tuyen Quang province. Vietnam Towards Sustain Develop Sustain (Switzerland). <https://doi.org/10.3390/SU12083170>
- Nodin MN, Mustafa Z, Hussain SI (2022) Assessing rice production efficiency for food security policy planning in Malaysia: a non-parametric bootstrap data envelopment analysis approach. *Food Policy*. <https://doi.org/10.1016/j.foodpol.2021.102208>
- Nyamahirwa DMA, Awotide BA, Kusinza DB, Bishikwabo VK, Mignouna J, Bamba Z, Donsop Nguetzet PM (2022) A comparative analysis of technical efficiency and profitability of agribusiness and non-agribusiness enterprises in Eastern DRC. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su14148384>
- Ozden A, Ozer OO (2019) Environmental and production efficiency calculation in Turkish agriculture. In: *Journal of Environmental Protection and Ecology* (Vol. 20, Issue 4).
- Page MJ, Moher D, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McKenzie JE (2021) PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*. <https://doi.org/10.1136/bmj.n160>

- Pan WT, Zhuang ME, Zhou YY, Yang JJ (2021) Research on sustainable development and efficiency of China's E-Agriculture based on a data envelopment analysis-Malmquist model. *Technol Forecast Soc Change*. <https://doi.org/10.1016/j.techfore.2020.120298>
- Pang J, Chen X, Zhang Z, Li H (2016) Measuring eco-efficiency of agriculture in China. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su8040398>
- Papadopoulou A, Ragkos A, Theodoridis A, Skordos D, Parissi Z, Abraham E (2021) Evaluation of the contribution of pastures on the economic sustainability of small ruminant farms in a typical Greek area. *Agronomy*. <https://doi.org/10.3390/agronomy11010063>
- Payandeh Z, Jahanbakhshi A, Mesri-Gundoshmian T, Clark S (2021) Improving energy efficiency of barley production using joint data envelopment analysis (Dea) and life cycle assessment (lca): Evaluation of greenhouse gas emissions and optimization approach. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su13116082>
- Pereira Domingues Martinho VJ (2020) Comparative analysis of energy costs on farms in the European Union: a nonparametric approach. *Energy*. <https://doi.org/10.1016/j.energy.2020.116953>
- Pishgar-Komleh SH, Čechura L, Kuzmenko E (2021) Investigating the dynamic eco-efficiency in agriculture sector of the European Union countries. *Environ Sci Pollut Res* 28(35):48942–48954. <https://doi.org/10.1007/S11356-021-13948-W/FIGURES/3>
- Purvis B, Mao Y, Robinson D (2019) Three pillars of sustainability: in search of conceptual origins. *Sustain Sci* 14(3):681–695. <https://doi.org/10.1007/s11625-018-0627-5>
- Raheli H, Rezaei RM, Jadidi MR, Mobtaker HG (2017) A two-stage DEA model to evaluate sustainability and energy efficiency of tomato production. *Inform Process Agriculture* 4(4):342–350. <https://doi.org/10.1016/j.inpa.2017.02.004>
- Ramezani M, Dourandish A, Jaghdani TJ, Aminizadeh M (2022) The influence of dense planting system on the technical efficiency of saffron production and land use sustainability: empirical evidence from Gonabad County Iran. *Agriculture (Switzerland)*. <https://doi.org/10.3390/agriculture12010092>
- Ramos de Oliveira AL, Braga Marsola K, Milanez AP, LiegeFatoreto RS (2022) Performance evaluation of agricultural commodity logistics from a sustainability perspective. *Case Stud Trans Policy* 10(1):674–685. <https://doi.org/10.1016/j.cstp.2022.01.029>
- Ransom CJ, Jolley VD, Blair TA, Sutton LE, Hopkins BG (2020) Nitrogen release rates from slow-And controlled-release fertilizers influenced by placement and temperature. *PLoS ONE* 15:1–21. <https://doi.org/10.1371/journal.pone.0234544>
- Rebolledo-Leiva R, Angulo-Meza L, Iriarte A, González-Araya MC (2017) Joint carbon footprint assessment and data envelopment analysis for the reduction of greenhouse gas emissions in agriculture production. *Sci Total Environ* 593–594:36–46. <https://doi.org/10.1016/j.scitotenv.2017.03.147>
- Rebolledo-Leiva R, Angulo-Meza L, Iriarte A, González-Araya MC, Vásquez-Ibarra L (2019) Comparing two CF+DEA methods for assessing eco-efficiency from theoretical and practical points of view. *Sci Total Environ* 659:1266–1282. <https://doi.org/10.1016/j.scitotenv.2018.12.296>
- Reig-Martínez E, Gómez-Limón JA, Picazo-Tadeo AJ (2011) Ranking farms with a composite indicator of sustainability. *Agric Econ* 42(5):561–575. <https://doi.org/10.1111/j.1574-0862.2011.00536.x>
- Ren C, Li R, Guo P (2017) Two-stage DEA analysis of water resource use efficiency. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su9010052>
- Ren F, Tian Z, Chen H, Shen Y (2021) Energy consumption, CO2 emissions, and agricultural disaster efficiency evaluation of China based on the two-stage dynamic DEA method. *Environ Sci Pollut Res* 28(2):1901–1918. <https://doi.org/10.1007/s11356-020-09980-x>
- Rodrigues WS, Mauad JRC, Vogel E, Sabbag OJ, Ruviano CF (2019) Sustainability and technical efficiency of fish hatcheries in the STATE of MATO GROSSO do SUL, Brazil. *Aquaculture* 500:228–236. <https://doi.org/10.1016/j.aquaculture.2018.10.024>
- Rybaczewska-Błazejowska M, Gierulski W (2018) Eco-efficiency evaluation of agricultural production in the EU-28. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su10124544>
- Saputri VHL, Sutopo W, Hisjam M, Ma'aram A (2019) Sustainable agri-food supply chain performance measurement model for GMO and Non-GMO using data envelopment analysis method. *Appl Sci (Switzerland)*. <https://doi.org/10.3390/app9061199>
- Sarkhosh-Sara A, Tavassoli M, Heshmati A (2020) Assessing the sustainability of high-, middle-, and low-income countries: a network DEA model in the presence of both zero data and undesirable outputs. *Sustain Prod Consum* 21:252–268. <https://doi.org/10.1016/j.spc.2019.08.009>

- Sarkis J (2007) Preparing Your Data for DEA. In J. Zhu & W. D. Cook (Eds.), *Modeling Data Irregularities and Structural Complexities in Data Envelopment Analysis* (pp. 305–320). Springer US. https://doi.org/10.1007/978-0-387-71607-7_17
- Seiford LM, Zhu J (1999) Infeasibility of super-efficiency data envelopment analysis models. *INFOR Journal* 37(2):174–187. <https://doi.org/10.1080/03155986.1999.11732379>
- Seo Y, Umeda S (2021) Evaluating farm management performance by the choice of pest-control sprayers in rice farming in Japan. *Sustainability (switzerland)* 13(5):1–10. <https://doi.org/10.3390/su13052618>
- Shahraki AS, Ahmadi NA, Safdari M (2019) A new approach to evaluate the economic efficiency and productivity of agriculture sector. *Appl Window Data Envelop Anal (WDEA)* 2(3):145–160
- Sharma S (2022) Environmental efficiency in South Asian agriculture: a potential of reducing CO2 emissions and fertilizers usage. *J Public Affairs*. <https://doi.org/10.1002/pa.2327>
- Sherzod B, Kim KR, Lee SH (2018) Agricultural transition and technical efficiency: an empirical analysis of wheat-cultivating farms in Samarkand Region Uzbekistan. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su10093232>
- Singh P, Singh G, Sodhi GPS, Benbi DK (2021) Accounting carbon footprints and applying data envelopment analysis to optimize input-induced greenhouse gas emissions under rice-wheat cropping system in North-Western India. *J Soil Sci Plant Nutr* 21(4):3030–3050. <https://doi.org/10.1007/s42729-021-00587-w>
- Singh P, Singh G, Sodhi GPS, Sharma S (2021) Energy optimization in wheat establishment following rice residue management with Happy Seeder technology for reduced carbon footprints in north-western India. *Energy* 230:120680. <https://doi.org/10.1016/j.energy.2021.120680>
- Singh G, Singh P, Sodhi GPS, Tiwari D (2021) Energy auditing and data envelopment analysis (DEA) based optimization for increased energy use efficiency in wheat cultivation (*Triticum aestivum L*) in north-western India. *Sustain Energy Technol Assess*. <https://doi.org/10.1016/j.seta.2021.101453>
- Sintori A, Liontakis A, Tzouramani I (2019) Assessing the environmental efficiency of greek dairy sheep farms: GHG emissions and mitigation potential. *Agriculture* 9(2):28. <https://doi.org/10.3390/agriculture9020028>
- Skevas T, Serra T (2016) The role of pest pressure in technical and environmental inefficiency analysis of Dutch arable farms: an event-specific data envelopment approach. *J Prod Anal* 46(2–3):139–153. <https://doi.org/10.1007/s11123-016-0476-0>
- Streimikis J, Miao Z, Balezentis T (2021) Creation of climate-smart and energy-efficient agriculture in the European Union: pathways based on the frontier analysis. *Bus Stratag Environ* 30(1):576–589. <https://doi.org/10.1002/bse.2640>
- Streimikis J, Saraji MK (2021) Green productivity and undesirable outputs in agriculture: a systematic review of DEA approach and policy recommendations. *Econom Res Ekonomika Istrazivanja*. <https://doi.org/10.1080/1331677X.2021.1942947>
- Streimikis J, Yu Z, Zhu N, Balezentis T (2022) Achievements of the European Union member states toward the development of sustainable agriculture: a contribution to the structural efficiency approach. *Technol Forecast Soc Change*. <https://doi.org/10.1016/j.techfore.2022.121590>
- Sui F, Yang Y, Zhao S (2022) What affects the production technology of labor-intensive agricultural industries in the context of labor aging? An Empirical Study Based on the Garlic Prod Lanling Sustain (Switzerland). <https://doi.org/10.3390/su14010048>
- Sánchez-Zamora P, Gallardo-Cobos R (2019) Diversity, disparity and territorial resilience in the context of the economic crisis: an analysis of rural areas in Southern Spain. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su11061743>
- Sánchez-Zamora P, Gallardo-Cobos R (2020) Territorial cohesion in rural areas: an analysis of determinants in the post-economic crisis context. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su12093816>
- Tan X, Na S, Guo L, Chen J, Ruan Z (2019) External financing efficiency of rural revitalization listed companies in China-based on two-stage DEA and grey relational analysis. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su11164413>
- Tang X, Lu C, Meng P, Cheng W (2022) Spatiotemporal evolution of the environmental adaptability efficiency of the agricultural system in China. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su14063685>
- Tetteh Anang B, Alhassan H, Danso-Abbeam G (2020) Estimating technology adoption and technical efficiency in smallholder maize production: a double bootstrap DEA approach. *Cogent Food & Agriculture* 6(1):1833421. <https://doi.org/10.1080/23311932.2020.1833421>

- Theodoridis AM, Psychoudakis A (2008) Efficiency measurement in Greek dairy farms: Stochastic frontier vs data envelopment analysis. *Int J Econom Sci Appl Res (IJESAR)* 1(2):53–66
- Thompson RG, Dharmapala PS, Rothenberg LJ, Thrall RM (1994) DEA ARs and CRs applied to worldwide major oil companies. *J Prod Anal* 5(2):181–203. <https://doi.org/10.1007/BF01073854>
- Thompson RG, Dharmapala PS, Rothenberg LJ, Thrall RM (1996) DEA/AR efficiency and profitability of 14 major oil companies in U.S. exploration and production. *Comput Operat Res* 23(4):357–373. [https://doi.org/10.1016/0305-0548\(95\)00044-5](https://doi.org/10.1016/0305-0548(95)00044-5)
- Thompson RG, Dharmapala PS, Thrall RM (1995) Linked-cone DEA profit ratios and technical efficiency with application to Illinois coal mines. *Int J Prod Econ* 39(1–2):99–115. [https://doi.org/10.1016/0925-5273\(94\)00064-H](https://doi.org/10.1016/0925-5273(94)00064-H)
- Thrall RM (1996) Chapter 5 Duality classification and slacks in DEA. *Ann Operat Res* 66:109–138
- Tian D, Zhao F, Mu W, Kanianska R, Feng J (2016) Environmental efficiency of chinese open-field grape production: an evaluation using data envelopment analysis and spatial autocorrelation. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su8121246>
- Tsaples G, Papathanasiou J (2021) Data envelopment analysis and the concept of sustainability: a review and analysis of the literature. *Renew Sustain Energy Rev* 138:110664. <https://doi.org/10.1016/j.rser.2020.110664>
- Turner I, Heidari D, Pelletier N (2022) Environmental impact mitigation potential of increased resource use efficiency in industrial egg production systems. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2022.131743>
- 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*. <https://doi.org/10.1007/s11356-020-09533-2/Published>
- United Nations (2015) Sustainable Development Goals. <https://sdgs.un.org/goals>
- Varela-Candamio L, Calvo N, Novo-Corti I (2018) The role of public subsidies for efficiency and environmental adaptation of farming: a multi-layered business model based on functional foods and rural women. *J Clean Prod* 183:555–565. <https://doi.org/10.1016/j.jclepro.2018.02.109>
- Vlontzos G, Niavis S, Pardalos P (2017) Testing for environmental Kuznets curve in the EU agricultural sector through an Eco-(in)efficiency index. *Energies*. <https://doi.org/10.3390/en10121992>
- Vlontzos G, Pardalos PM (2017) Assess and prognosticate green house gas emissions from agricultural production of EU countries, by implementing, DEA Window analysis and artificial neural networks. *Renew Sustain Energy Rev* 76:155–162
- Waltman L, van Ecken NJ (2010) VOSViewer: Visualizing Scientific Landscapes. <https://www.vosviewer.com/>
- Wang C-N, Dang T-T, Tibo H, Duong D-H (2021) Assessing renewable energy production capabilities using dea window and fuzzy TOPSIS model. *Symmetry* 13(2):334. <https://doi.org/10.3390/sym13020334>
- Wang CN, Lin HS, Hsu HP, Le VT, Lin TF (2016) Applying data envelopment analysis and grey model for the productivity evaluation of Vietnamese agroforestry industry. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su8111139>
- Wang Y, Shi L, Zhang H, Sun S (2017) A data envelopment analysis of agricultural technical efficiency of Northwest Arid Areas in China. *Front Agricultural Sci Eng* 4(2):195–207
- Wang S, Tian N, Dai Y, Duan H (2022) Measurement of resource environmental performance of crop planting water consumption based on water footprint and data enveloped analysis. *Water Resour Manage* 36(2):641–658. <https://doi.org/10.1007/s11269-021-03045-5>
- Watto M, Muger A (2019) Wheat farming system performance and irrigation efficiency in Pakistan: a bootstrapped metafrontier approach. *Int Trans Oper Res* 26(2):686–706. <https://doi.org/10.1111/itor.12314>
- Wu G, Fan Y, Riaz N (2022) Spatial analysis of agriculture ecological efficiency and its influence on fiscal expenditures. *Sustainability* 14(16):9994. <https://doi.org/10.3390/su14169994>
- Xiao X, Fan M, Wang E, Chen W, Wei G (2017) Interactions of plant growth-promoting rhizobacteria and soil factors in two leguminous plants. *Appl Microbiol Biotechnol* 101(23–24):8485–8497. <https://doi.org/10.1007/s00253-017-8550-8>
- Xing Z, Wang J, Zhang J (2018) Expansion of environmental impact assessment for eco-efficiency evaluation of China's economic sectors: an economic input-output based frontier approach. *Sci Total Environ* 635:284–293. <https://doi.org/10.1016/j.scitotenv.2018.04.076>
- Xu P, Jin Z, Tang H (2022) Influence paths and spillover effects of agricultural agglomeration on agricultural green development. *Sustainability (Switzerland)*. <https://doi.org/10.3390/su14106185>

- Xu T, You J, Li H, Shao L (2020) Energy efficiency evaluation based on data envelopment analysis: a literature review. *Energies* 13(14):3548. <https://doi.org/10.3390/en13143548>
- Yan Z, Zhou W, Wang Y, Chen X (2022) Comprehensive analysis of grain production based on three-stage super-SBM DEA and machine learning in Hexi Corridor China. *Sustainability* (Switzerland). <https://doi.org/10.3390/su14148881>
- Yang L, Zhou Y, Meng B, Li H, Zhan J, Xiong H, Zhao H, Cong W, Wang X, Zhang W, Lakshmanan P, Deng Y, Shi X, Chen X, Zhang F (2022) Reconciling productivity, profitability and sustainability of small-holder sugarcane farms A combined life cycle and data envelopment analysis. *Agricultural Syst* 199:103392. <https://doi.org/10.1016/j.agsy.2022.103392>
- Yang Y, Zhuang Q, Tian G, Wei S (2019) A management and environmental performance evaluation of China's family farms using an ultimate comprehensive cross-efficiency model (UCCE). *Sustainability* (Switzerland). <https://doi.org/10.3390/su11010006>
- Zahm F, Viaux P, Vilain L, Girardin P, Mouchet C (2008) Assessing farm sustainability with the IDEA method - from the concept of agriculture sustainability to case studies on farms. *Sustain Dev* 16(4):271–281. <https://doi.org/10.1002/sd.380>
- Zhang M, Cui WK, Zhang YJ, Xu YH (2021) Research on world food production efficiency and environmental sustainability based on entropy-DEA model. *Complexity*. <https://doi.org/10.1155/2021/8730264>
- Zhang Y, Jiang Y, Wei L (2021) Evaluation and reconstruction of world food security system. *IOP Conf Series: Earth and Environ Sci* 792:012032. <https://doi.org/10.1088/1755-1315/792/1/012032>
- Zhou H, Yang Y, Chen Y, Zhu J (2018) Data envelopment analysis application in sustainability: The origins, development and future directions. *Eur J Oper Res* 264(1):1–16. <https://doi.org/10.1016/j.ejor.2017.06.023>
- Ziętek-Kwaśniewska K, Zuba-Ciszewska M, Nucińska J (2022) Technical efficiency of cooperative and non-cooperative dairies in Poland: toward the first link of the supply Chain. *Agriculture* (Switzerland). <https://doi.org/10.3390/agriculture12010052>

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