Agricultural Water Management 309 (2025) 109314

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Economic efficiency of drip and flood irrigation. Comparative analysis at farm scale using DEA

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ARTICLE INFO

Handling Editor - Dr. Brent Clothier.

Keywords:
Data envelopment analysis
Water efficiency
Drip irrigation
Flood irrigation

ABSTRACT

In recent decades, there has been a massive replacement of flood irrigation with drip irrigation throughout the world. Numerous studies have been published on the efficiency of these techniques in terms of water savings, but few works have paid attention to their economic efficiency at farm scale. In this research, a two-stage methodology has been used for this purpose, developed in three irrigated areas of the region of Valencia (Eastern Spain). In the first stage, interviews were conducted with experts from irrigation communities and cooperatives, and in the second stage, an efficiency analysis was carried out using Data Envelopment Analysis (DEA). It is concluded that, although the cultivation costs of drip irrigation are lower and the technology gap (TGR^K) is smaller than flood irrigation, there is much room for improvement. Policies to promote the installation of localised irrigation should include complementary measures to ensure the viability of modernised farms.

1. Introduction

The agricultural sector consumes almost 70 % of all water withdrawals and up to 95 % in some developing countries (FAO, 2020). This fact, in a global context of shrinking water resources, due to demographic growth, increasing food demand and climate change, has put the political focus on improving agricultural water use and management (Steduto et al., 2017). Consequently, during the last decades, many countries have implemented policies to promote new technologies to improve irrigation efficiency. This process, developed with significant public sector support (Venot et al., 2017; Molle and Sanchis-Ibor, 2019), has focused almost exclusively on implementing water conservation technologies. As a result, the expansion of pressurisation of irrigation networks has meant an unprecedented technological change in many countries (ICID, 2024).

Water conservation technologies include sprinkler or drip irrigation systems, laser field levelling, piped distribution systems, canal lining and other infrastructure improvements to irrigation and distribution systems. Traditionally, the aim of this change is to increase irrigation efficiency, which will reduce the demand on water resources, and lead to an improvement in both productivity and farmers' incomes (Gleick et al., 2011; Pérez-Blanco et al., 2020). Some authors expect that the water-saving potential of new technologies could offset the effects of climate change and population growth in the future (Fader et al., 2016).

However, against the consideration of pressurized irrigation as water saving technique, scientific literature has identified some misconceptions surrounding the expected benefits of its promotion. From the first references in the 60's (Molden, 1997), numerous authors have analyzed and disputed the effectiveness of pressurized irrigation to save water and face water scarcity, but also its economic, environmental and social implications. Case studies around the world demonstrate that in certain circumstances irrigation efficiency promotion through water-saving irrigation technologies can lead to some unintended consequences (Ward and Pulido-Velazquez, 2008; Törnqvist and Jarsjö

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https://doi.org/10.1016/j.agwat.2025.109314
Received 11 October 2024; Received in revised form 24 December 2024; Accepted 12 January 2025
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2011; Van der Kooij et al., 2013; Lankford, 2012; Berbel et al., 2014; Lopez-Gunn et al., 2012; Perry and Steduto, 2017; Venot et al., 2014; Perez Blanco et al., 2020), usually referenced as irrigation modernization paradoxes (Rodríguez-Díaz et al., 2011; Scott et al., 2014; Grafton et al., 2018). This debate has disclosed that the analysis of the effects of pressurized irrigation adoption requires a more holistic approach, because in different world regions and spatial scales, multiple effects -that could be interconnected- have been detected (Lankford et al., 2020).

Although most publications on the consequences of irrigation technology change have focused on the effects on savings, this process has many other consequences that have received little attention (Gómez-Limón and Picazo-Tadeo, 2012; Sanchis-Ibor et al., 2016; Ortega Reig et al., 2017; Berbel et al., 2019; Sampedro, 2020). The process of technological change has an influence on the way water is managed, on labour demands, on the use of energy needed to apply water, among others. These organisational changes have effects on irrigation costs, which generally increase, on the one hand, because of the need to amortise the unsubsidised part of the investment and, on the other hand, because of the increase in operating costs due to the use of energy needed for pressurisation (García Mollá et al., 2017; Hardy et al., 2012; Jackson et al., 2010; Playan et al., 2024). Generous subsidies for the investments needed for the installation of the techniques have mitigated the increases in irrigation costs (Venot et al., 2017; Molle and Sanchis-Ibor, 2019).

The change of irrigation technique also entails important changes in the rest of the cultivation practices and, as a consequence, in cultivation costs. The increase in soil moisture caused by these techniques transforms agriculture into an input-output intensive production system (Pérez-Blanco et al., 2021). The installation of sparing techniques allows the use of centralised fertilisation in WUAs, which increases the nutrient use efficiency as well as crop productivity and yield quality (Sravani et al., 2020). In field experiments Moursy et al. (2023) show that the increase in profit is greater than the increase in irrigation costs for virtually all summer crops. Although not many papers evaluate changes in cultivation costs due to changes in irrigation technique, most publications indicate that irrigation modernisation leads to an increase in productivity and yield quality, whereby the increase in revenue outweighs the increase in irrigation costs, resulting in an increase in profit (Pérez-Blanco et al., 2020; Ruíz-Rodriguez, 2017).

There seems therefore to be sufficient evidence to assume that the shift towards water-saving technologies has an impact on both revenues and cultivation costs. The combined impact of these increases on farm profitability may therefore be mixed. Although more and more research is being carried out on the consequences of the adoption of water-saving technologies, it is necessary to know in a more exhaustive way the effects it has had on the economy of irrigators, as this is what will finally determine the viability of the farms.

This research aims to improve knowledge on the economic effects of the change in irrigation techniques on irrigated plots in the region of Valencia (Spain). It proposes to accomplish this task in two stages, the first one aimed at characterizing the differences in cultivation practices associated with different irrigation techniques (flood irrigation or drip irrigation) and the second one at evaluating the economic efficiency of these techniques. To this end, we have used a mixed methodology that combines interviews with experts in the irrigation sector to evaluate the effects on cultivation costs and income due to a change in irrigation technique, with an analysis of the efficiency for different plots with different irrigation techniques in the same area. On the one hand, we will determine the changes in agricultural work due to the change in irrigation technique and we will evaluate the differences in production costs and income of the plots that have adopted drip irrigation and those that have not. On the other hand, how these changes in crop costs and income influence the efficiency of drip-irrigated and surface-irrigated plots will be quantified using data envelopment analysis (DEA). The use of traditional DEA can present problems in this case, due to the heterogeneity of the cropping techniques used in different irrigated farms. To overcome this limitation, this paper proposes the use of metafrontiers as a variant to the calculation of efficiency using traditional DEA.

2. Case study

The study area is located in the region of Valencia, on the Spanish Mediterranean coast. This region has an agricultural area of 590,190 ha, of which 249,706 ha are irrigated. The climatic and soil characteristics of the region favour the cultivation of fruit and vegetables. Citrus crops occupy 155,785 ha, all of which are irrigated. In recent decades, the crisis in the citrus sector has led to an increase in the cultivated area of other irrigated fruit trees, among which the cultivation of persimmon (14,639 ha) stands out. These crops are the predominant ones, almost exclusive, in the irrigated systems where the interviews of this research were carried out.

The region has a growing structural water scarcity due to the increasing agricultural and urban demand, especially for tourism, and the decrease in resources due to climate change. Public administrations and farmers' and irrigators' associations made a clear commitment to irrigation modernisation since the late 1980s, encouraged by the cyclic droughts (Sanchis-Ibor et al., 2017). A significant part of the costs of the necessary investments have been subsidised by different public administrations (Sanchis-Ibor et al., 2021). As a result of this process, 73 % of the 289,499 ha irrigated in the region now have infrastructure for localised irrigation, which is almost entirely drip irrigation (MAFF, 2023). Most of the irrigated areas are collectively managed by water users's associations called irrigation communities (IC).

The technicians and managers interviewed belong to the IC Séquia Reial del Xúquer, which irrigates 20,000 ha in 21 municipalities; the IC Riu d'Alcoi, which irrigates 2500 ha in 16 municipalities; the IC of Vilareal, which irrigates some 2600 ha in three municipalities; and the CANSO cooperative which, among other activities, has a cultivation section in which the members entrust all the cultivation work to the cooperative (Fig. 1). CANSO currently manages more than 200 ha of citrus and persimmon crops in the municipality of L'Alcúdia. In addition, the cooperative offers technical advice to member farmers.

Agriculture in these areas has structural characteristics that make it difficult for farms to be competitive in the context of increasingly globalised agricultural markets. Landholdings are small (mean size of farms is 5.5 ha and the mean size of irrigation plots is 0.52 ha) so farming activity is hardly profitable for professional farmers (Sanchis-Ibor et al., 2020). Part-time farming accounts for over 40 % of the area, an important percentage of the professionals are formally retired. The low profitability of farms means that there is no generational handover, as young people prefer other jobs with higher incomes. The average age of farmers in the region is 64,4 years.

3. Methodology

A two-stage methodology was used. In the first stage, interviews with experts in the sector and in the second stage, analysis of data on income and costs of irrigated farms with the two irrigation techniques.

3.1. *Assessment of cultivation costs and revenues: differences between drip and flood irrigation*

The change of irrigation technique has a clear impact on the costs of irrigation, but the modification of cultivation techniques resulting from the change of technique also changes the costs of cultivation. In order to evaluate changes in cultivation costs and income, in-depth semi-structured interviews were conducted with experts in irrigation management belonging to irrigation communities and cooperatives in the region of Valencia. Some of the interviewed entities have a long experience with pressurised irrigation while others are still in a period of expansion. In

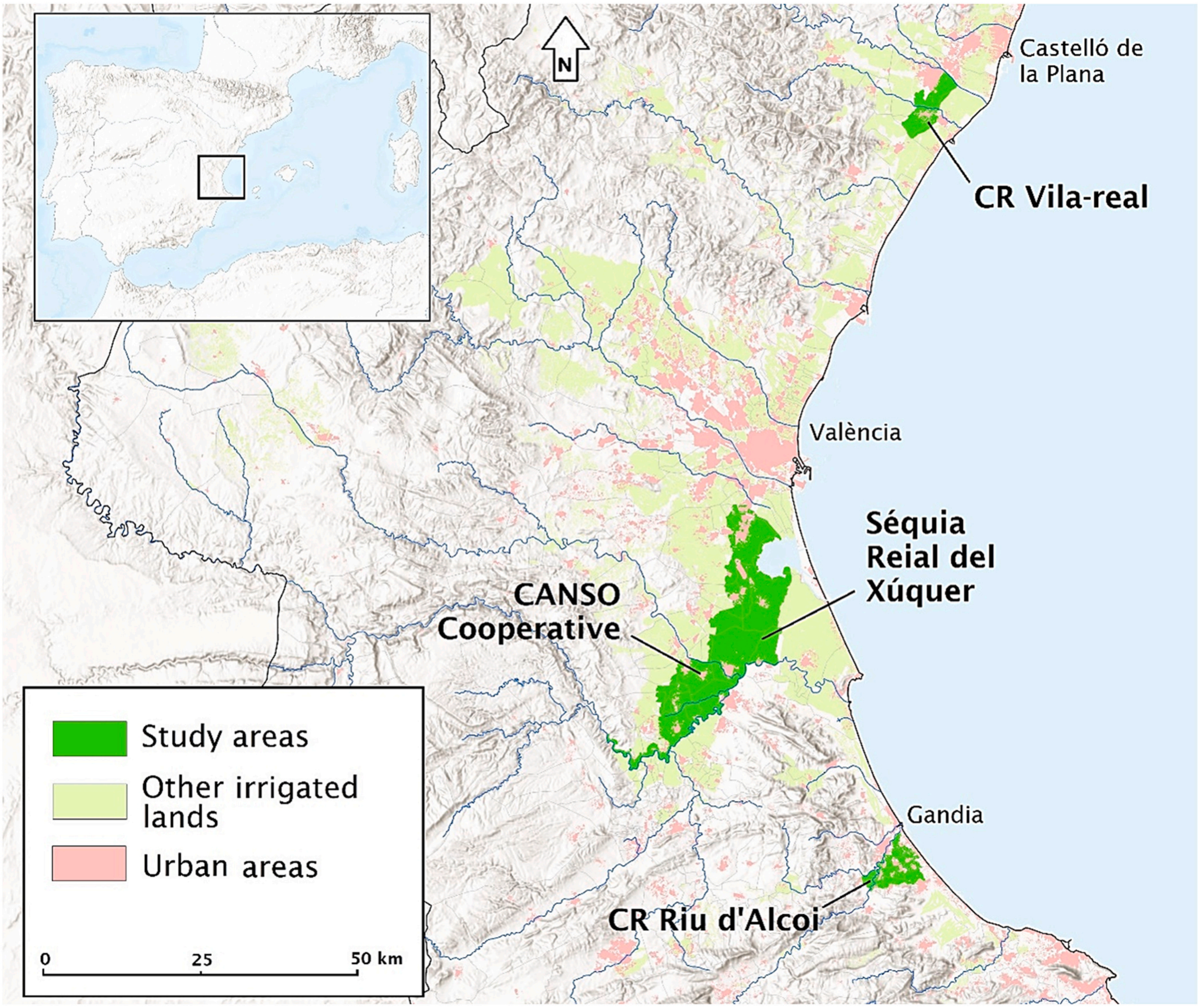

Fig. 1. Location of the study areas.

the interviews they were asked about the differences in costs and revenues of the two irrigation techniques and about the advantages and disadvantages of the two irrigation systems. The cultivation costs depend on the tasks that differ in the two irrigation techniques and which we have grouped into the following:

a) Irrigation costs: these are collected by the irrigation community. In general, the entities charge a fixed amount to cover fixed costs and a variable amount, which in the case of drip irrigation is billed per cubic metre and in the case of flood irrigation is billed per irrigation turn (García-Mollá et al., 2017). All the interviewed entities have received subsidies from different public administrations for the change of irrigation technique. The costs of the investments and the subsidies provided are highly variable and depend on the percentage of subsidies and the complexity of the installations. Generally, the irrigation entity carries out all the installations up to the plot level. The cost of these investments is passed on to the irrigator in the form of annual instalments. The irrigator carries out and pays for all the necessary investments inside the plot (Sanchis Ibor et al., 2017).
b) Fertilisation: In irrigation entities with localised irrigation, it is common for the irrigation communities to carry out the fertilisation through a centralised fertigation system. Farmers using traditional irrigation buy their own fertilisers and pay for the labour needed to apply them or apply them themselves.
c) Herbicides: Includes the cost of the products and the labour required for their application.
d) Phytosanitary products and pruning and shredding: These include the cost of the necessary treatments and their application and the labour costs of pruning and shredding the remains. These costs have been unified because there are usually no differences in the cultivation work carried out with the two techniques.

3.2. *Calculating efficiency through DEA*

In order to evaluate the changes in efficiency due to the change of irrigation technique of the plots in the region of Valencia, 202 farms were interviewed. This is a representative sample of the universe of this geographical area. All of them belong to a service cooperative that carries out all the cultivation tasks except for irrigation, which is carried out by an irrigation community. The structural characteristics of agriculture in the area mean that many farmers opt for the cooperative to carry out all the tasks. Apart from the payment to the service cooperative, the only cultivation cost borne by the farmers is the payment to the irrigation entity. Most of the farms have made the change from flood irrigation to drip irrigation, but some owners have preferred to continue using the traditional flood irrigation.

Changes in crop costs and income resulting from changing irrigation technique have an impact on farm efficiency. Although DEA has been successfully used in research related to wastewater treatment (Lorenzo-Toja et al., 2015; Longo et al., 2018; Maziotis and Molinos-Senante, 2023), to the degree of compliance with SDG6 (Alves Pereira and Cunha Marques, 2021), to assess the link between social capital, participatory management and irrigation efficiency (Suwanmaneepong et al., 2024), assessing the water use efficiency of water user associations (Mahdhi et al., 2021) and even in the assessment of water savings from irrigation modernisation policies (García-Mollá et al., 2021), it has not been used to evaluate the changes in efficiency derived from the different cropping tasks of flood and drip irrigation.

3.2.1. *Method: DEA metafrontier model*

The concept of efficiency is based on production and distance theories used for the construction of a production function to determine the level of efficiency of each of the observations that make up the sample under study (decision making units, DMUs). The most widespread techniques are non-parametric linear programming models (DEA, data envelopment analysis) and regression techniques based on the estimation of error inefficiency (SFA, Stochastic Frontier Analysis). However, DEA has a clear superiority over SFA both because of the flexibility provided by the absence of a pre-defined functional form and the possibility of working with multiple inputs/outputs as well as the absence of stochastic errors. Both methodologies presuppose the existence of homogeneity among the DMUs that make up the sample. However, the irrigation techniques applied to the different crops may present intrinsic differences that invalidate their application. In order to overcome this limitation, this research proposes the use of the metafrontier, as a variant of the original DEA, where the possible existence of dissimilarities between the DMUs analyzed can be contemplated. Likewise, the scientific community has validated metafrontiers in areas where it has been necessary to consider the presence of heterogeneity, citing, among others, the analysis of efficiency in the water industry (Molinos-Senante et al., 2023), the change in productivity of Brazilian water utilities (Tourinho et al., 2023), irrigation technologies applied to coffee cultivation (Ho et al., 2022), to assess water use efficiency in the framework of the SDGs (Lozano and Borrego-Marín, 2024a) or to study the environmental efficiency of wheat cultivation in Spain (Lozano et al., 2024b).

DEA facilitates the calculation of the relative efficiency of each DMU by maximizing/minimizing a production function constructed with the inputs and outputs that define it. Building on the pioneering work of Farrell (1957), Charnes et al. (1978) propose a linear programming model to maximize outputs with the available resources (output orientation, *oo*) or vice versa, to minimize inputs to obtain a given level of production (input orientation, *io*), all in an environment of constant returns to scale. In order to provide greater flexibility, Banker et al. (1984) introduce the possibility that inputs/outputs may vary in different proportions, variable returns to scale (VRS), which better approximates actual events.

In the field of DEA, the metafrontier, developed by Battesse and Rao (2002) and Battesse et al. (2004), provides an optimal solution to the problem of DMU heterogeneity, facilitating the determination of the most appropriate form of management, while assessing efficiency. First, a frontier is constructed for each of the groupings considered (TE^K), i.e., the distance between each observation and the efficient frontier of its own group is calculated, thus avoiding the heterogeneity of the sample when comparing units belonging to the same typology. Subsequently, ignoring the different operational characteristics, the metafrontier (TE) is constructed with all the DMUs in the sample where, as an umbrella, all the frontiers of the technologies analyzed are included (Fig. 2).

From TE^K and TE we obtain the technology gap ratio (TGR^K), which determines the most appropriate form of management (Eq. 1), i.e., the closest to the metafrontier and, therefore, the most efficient (O'Donnell et al., 2008). In this way, it is possible to differentiate the origin of the overall inefficiency (TE) of each DMU, discerning whether it is due to poor group management (TE^K) or inadequate technology (TGR^K), Eq. 2.

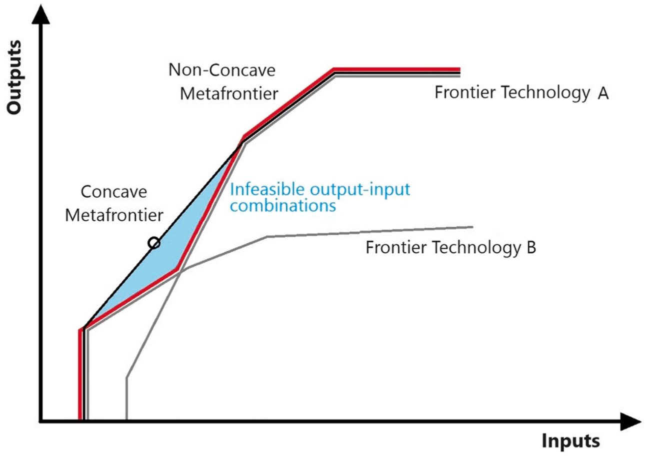

Fig. 2. Concave and Non-concave metafrontier.

$$TGR^K = \frac{TE}{TE^K} \tag{1}$$

$$TE = TE^k \cdot TGR^K \tag{2}$$

However, as shown in Fig. 2, the application of this methodology could contemplate DMUs outside the sample evaluated, i.e., infeasible input-output combinations. Following Tiedemann et al. (2011), we propose the construction of an efficient frontier that includes only the DMUs under analysis, a non-concave metafrontier. This choice makes it possible to adjust the frontier to the observations of the sample, avoiding the non-existent combinations that arise in the construction of concave metafrontiers (blue area). Moreover, given the particularities of the analysis, it was decided to implement the *oo* y in a VRS environment.

The choice of oo is conditioned by the fact that farmers logically seek to maximise their income, with less scope for reducing the resources used. On the other hand, the VRS option contemplates the possibility that the level of inefficiency is due to an inadequate combination of resources (CRS) and/or the wrong choice of the scale of production, a very common problem in the environment analysed. In order to give robustness to this choice, the average scale efficiency (SE) has been calculated as the quotient between the average efficiency score CRS and the VRS, obtaining a value lower than 1.[5] The results take values greater than 1, where the excess over unity represents the level of inefficiency of the evaluated observation. The DeaR library implemented in the free software R studio (Coll-Serrano et al., 2018) has been used.

3.2.2. *Data*

The proposed research aims to obtain quantitative evidence of the changes in efficiency that occur when the irrigation technique is changed. The proposed methodology is very sensitive to the accuracy of the data used, being necessary, first, to eliminate those observations whose answers were incomplete, as well as the outliers that could distort the results. The farms were selected by simple probability sampling. All farms in the sample had all the accounting data necessary to run the DEA model. The sample was reduced to 171 farms distributed between the two forms of irrigation and crops proposed (Fig. 3). Surface irrigation represents 31.5 %, destined to citrus and persimmon crops, maintaining a weight similar to the reality of the area analyzed.

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[5] SE= Mean CRS Score/Mean VRS Score = 0.1297/0.5631 = 0.2304. At the individual level only 2 DMUs show an SE equal to 1

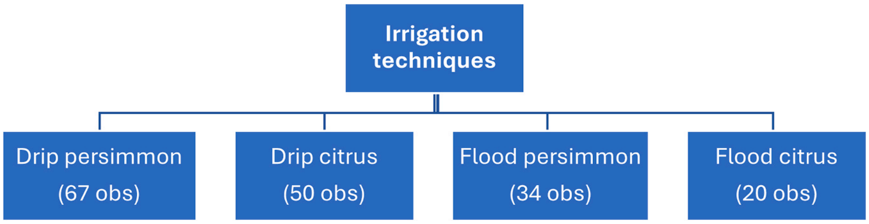

Fig. 3. Irrigation techniques, crops and observations made.

The DEA requires classifying the variables into inputs and outputs in order to be able to construct the production function necessary to apply the line programming model that will allow quantifying the efficiency of the observations that define the sample. The surveys carried out have facilitated the definition of 4 inputs valued in euros (fertilizers, phytosanitary products, machinery and labor, and irrigation costs) and 1 output (income per hectare) specific to each form of irrigation and crop (Table 1). Inputs are crop costs grouped by type of task. The variables selected are those typically employed in the evaluation of efficiency in agriculture using DEA, either in physical or monetary terms (Manogna and Mishra, 2022; Pishgar-Komleh et al., 2020; Singh et al., 2023; Liu et al., 2022). The choice of the output was motivated by the particularity of the income to be able to absorb the oscillations in production caused by climatic changes; it is a variable whose value is higher when the harvest is scarce, and vice versa.

On the other hand, our approach has not taken into account the existence of undesirable inputs or outputs to carry out the analysis. There is currently a debate on whether or not to adopt energy-saving technologies on unprofitable farms. We have chosen to calculate the economic efficiency, avoiding externalities, to get an idea of whether or not the change of technique is appropriate from the point of view of the farmer and the survival of the farm.

The appropriate use of the metafrontier requires first demonstrating that the proposed variables present statistically significant differences according to the form of irrigation. The choice of the Kruskal-Wallis test was motivated by the absence of a normal distribution of inputs/outputs, and by the need to choose between two more groups (Kruskal and Wallis, 1952). The null hypothesis (H_0) establishes that all observations belong to the same population, i.e., each of the variables chosen does not show significant differences between the groups analyzed. H_0 is accepted when the significance level obtained is greater than 0.05 ($p\text{-value} > 0.05$), and rejected otherwise (Table 1).

The results reveal the acceptance of the H_0 in labour and machinery ($p\text{-value} = 0.183$). It is shown that this variable is independent of the particularities of the four groups analyzed, forcing a reduction in the number of inputs (fertilizers, phytosanitary products and irrigation costs). The descriptive statistics that allow characterizing the sample are shown in Table 2.

Table 2 shows that there are no apparent differences between the groups analyzed, although the surface irrigated persimmon crops obtain higher income (286.63 mean), with lower irrigation and fertilizer costs (92.54 and 76.7 mean). In any case, it is evident that there is a great dispersion in crop costs in the different irrigation methods analyzed (SD sometimes exceeds 50 % of average values), even more so in the surface irrigation of citrus and persimmons. This is due to the fact that costs vary due to a large number of factors such as the pests or diseases that the crops may have or the farmers' preferences. This diversity is greater in traditionally irrigated crops, since in drip irrigation, fertilizer costs are centralized and less dispersed.

Table 1
Kruskal-Wallis test.

		Chi-Square (x^2)	Probability
Input	Fertilizers	44.826	0.000
	Phytosanitary products	24.418	0.000
	Labour + machinery	4.846	0.183
	Irrigation cost	35.816	0.000
Output	Income	14.97	0.001

Table 2
Descriptive statistics for inputs and outputs (2021–2022).

	Income	Fertilizers	Phitosanitary products	Irrigation costs
	Total			
Mean	248.67	171.99	538.11	113.46
SD	69.23	91.74	250.13	49.74
Max	453.99	423.78	1208.78	233.64
Min	94.44	10.20	45.25	9.77
	Drip persimmon			
Mean	244.51	178.48	583.72	129.50
SD	59.17	62.75	234.75	46.64
Max	453.99	294.36	1095.74	216.69
Min	129.95	49.94	197.04	37.73
	Drip citrus			
Mean	245.24	225.80	397.23	127.74
SD	66.42	98.97	182.22	51.55
Max	429.13	423.78	1075.16	233.64
Min	126.15	27.76	45.25	9.77
	Flood persimmon			
Mean	286.63	92.54	637.53	76.70
SD	73.67	72.51	273.84	31.53
Max	404.26	271.84	1208.78	129.94
Min	143.36	10.20	160.58	19.06
	Flood citrus			
Mean	206.63	150.80	568.51	86.52
SD	73.39	87.71	272.53	36.99
Max	343.36	374.24	1049.36	154.85
Min	94.44	33.61	119.47	27.94

4. Results and discussion

4.1. Economic costs of cultivation in flood and drip irrigation

Based on interviews with technicians, the costs of cultivation per unit of area have been evaluated. The estimated quantities appear in Table 3.

The costs of traditional irrigation are lower in all the entities interviewed than the costs of drip irrigation. This is due to the fact that the use of the energy necessary for the pressurization of the irrigation networks makes its cost higher. On the other hand, drip irrigation requires investments that also increase irrigation costs.

However, in all entities, cultivation costs are lower if drip irrigation is used. This is due, on the one hand, to the fact that fertilization is centralized when drip irrigation is used. The irrigation communities buy fertilizer in large quantities, which allows them to obtain better prices. In addition to traditional fertilizers, the irrigation entities' schedules include chelates, biostimulant, rooting, soil conditioner, complexed calcium… In these cases, the fertilizer is invoiced with the irrigation. Irrigators who continue to irrigate by the traditional system must buy their fertilizers and also pay for the application (or do it by themselves, what causes great discomfort to the older farmers). In recent years, the increase in the cost of mineral fertilizer has led the IC Riu d'Alcoi and the IC Vila-real to opt for organic fertilizer.

Table 3
Costs of cultivation in flood and drip irrigation.

	SRX		**Coop Canso**		**IC Riu Alcoi**		**IC Vila-Real**	
	Drip	Flood	Drip	Flood	Drip	Flood	Drip	Flood
Irrigation	504	480	937*	390	1.656*	1.176	1.284–2.196*	507
Fertilizers + fertilizers application	396	960	0	543		480–600	0	600
Herbicides	180	360	312	385	720–1.080	840–1.200	1.553 **	3.045 **
Phitosanitary products	600	600	600	600	240–360	240–360	0	0
Pruning and shredding	1.200	1.200	1.200	1.200	1.080	1.080	1.500	1.500
TOTAL	**2.880**	**3.600**	**3.049**	**3.118**	**3.936**	**4.116**	**4.793**	**5.652**

* Includes fertilizers.
** Includes the costs of applying all treatments, that is, herbicides and phytosanitary products.

The cost of herbicides and their application is also lower in entities that use localized irrigation. The interviewees indicated that in the case of drip irrigation, the area of soil on which herbicides are applied and the number of applications per year are reduced. Drip irrigation concentrates water application in a strip close to the tree and causes weeds to grow almost exclusively in this area. In addition, this area is mostly covered by the shade of the tree so weeds grow much less. Both herbicide products and labor are less in localized irrigation. On the other hand, phytosanitary treatments, pruning and shredding do not differ between the two irrigation techniques, except in the IC of Vila-real, where the planting frames are different between traditional irrigation, where there is a higher density, and drip irrigation, where the larger planting frames allow the mechanization of the tasks of treatment application and pruning.

Crop incomes are highly variable and unpredictable. Both production and prices vary from one variety to another and from one year to another so that it is difficult to know the differences between the income obtained with the two irrigation techniques. Production depends on many factors, such as the age of the plants, the planting frame, the rootstocks and varieties, the sprouting date, the location of the plot, etc. While some technicians point to an increase in production and quality, and therefore price, in production with drip irrigation, for others there is no difference between one technique and another. Some studies point to an increase in production (Ruíz-Rodriguez, 2017) but they are referred to a very specific area of the IC Séquia Reial del Xúquer.

In this study it was evaluated that drip irrigation achieves a production increase of 26’64 %. The general opinion is that the main advantage of drip irrigation is comfort, especially considering that in the area there is a high percentage of part-time farmers. This aspect is particularly important in an area where farm viability is low. For some interviewees in areas where there is drip irrigation, abandonment of plots is lower. Another advantage is that it allows irrigation in mountainous areas where it would not have been possible to irrigate with traditional irrigation. It is estimated that this occurs in about 20 % of the irrigated area of the IC Riu d’Alcoi. Seedlings grow better with drip irrigation, in areas with flood irrigation the need for more frequent irrigation than irrigation shifts means that water has to be provided manually by farmers.

For the managers and technicians of the entities interviewed, the main advantage of traditional irrigation is that they do not have to pay the amortization of the investment, which especially in the IC Riu d'Alcoi is very high. They have had many problems with the installation that was made with a previous governing board of the IC, with investment costs that doubled the initial budget. Another advantage of traditional irrigation is that it allows independent fertilization. The few professional farmers in the area opt for this technique because it allows them greater flexibility and they can perform their tasks while saving on labour costs. Another problem observed in the areas studied is the risk of clogging of the emitters, and the resulting effect on irrigation uniformity, so the filtration system implemented, and its maintenance is very important.

4.2. *Evaluation of efficiency based on irrigation technique*

The Kruskal-Wallis test confirmed the existence of four groups depending on the type of irrigation and product grown: drip_persimmon, drip_citrus, surface_persimmon, and surface_citrus. It was found that the three inputs and the chosen output operate under different technological boundaries. Following the proposed methodology, non-concave metrafrontier, the efficiency of each group, the metafrontier and the technological gap ratio have been calculated avoiding considering DMUs not existing in the sample. Table 4 shows the descriptive statistics of the results obtained, distinguishing the following rows: TE^K, technical efficiency[6] of group k; TE, technical efficiency with respect to the metafrontier; TGR^K, distance between the efficiency of group k and the metafrontier, representing the efficiency of the management method of each of the groups analyzed, the most appropriate being the one with the lowest value; EFF_TE^K, percentage of efficient DMUs in the frontier of group k; EFF_TE, percentage of efficient DMUs in the metafrontier; EFF_TE, percentage of efficient DMUs in the metafrontier, representing

Table 4
Mean values of the group efficiencies (TE^K), the metafrontier (TE), and the technology gap ratio (TGR^K).

	Drip persimmon				
	Mean	***SD***	***Max***	***Min***	***%EFF***
TE^K	1.794	0.404	2.928	1	
TE	1.896	0.440	3.302	1	
TGR^K	1.067	0.188	2.481	1	
EFF_TE^K	-	-	-	-	4.48 %
EFF_TE	-	-	-	-	1.49 %
	Drip citrus				
	Mean	***SD***	***Max***	***Min***	***%EFF***
TE^K	1.878	0.521	3.402	1	
TE	1.889	0.527	3.402	1	
TGR^K	1.005	0.015	1.058	1	
EFF_TE^K	-	-	-	-	2.00 %
EFF_TE	-	-	-	-	2.00 %
	Flood persimmon				
	Mean	***SD***	***Max***	***Min***	***%EFF***
TE^K	1.415	0.369	2.448	1	
TE	1.588	0.405	2.448	1	
TGR^K	1.100	0.053	1.197	1	
EFF_TE^K	-	-	-	-	11.76 %
EFF_TE	-	-	-	-	5.88 %
	Flood citrus				
	Mean	***SD***	***Max***	***Min***	***%EFF***
TE^K	1.441	0.426	2.266	1	
TE	2.391	0.844	4.544	1	
TGR^K	1.717	0.741	4.544	1	
EFF_TE^K	-	-	-	-	15.00 %
EFF_TE	-	-	-	-	0 %

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[6] Technical efficiency determines the ability to obtain the maximum output with the available inputs.

the efficiency of the management method of each of the groups analyzed, the most appropriate being the one with the lowest value; EFF_TE^{K}, percentage of efficient DMUs in the frontier of group k; EFF_TE, percentage of efficient DMUs in the metafrontier.

Firstly, we will analyse the efficiency ratios with respect to the group boundaries (TE^{K}). This data allows us to evaluate the efficiency of each farm with respect to the group with which it shares technology. The most efficient technologies are those that reach the value of unity and the inefficiency grows in the average in which the value of this indicator grows. It is observed that surface irrigation in both crops obtains the best levels of average technical efficiency (1.415 and 1.441 in persimmon and citrus, respectively), reaching the highest percentage of fully efficient farms (15 % in critics, and 11.76 % in persimmons). These results plummet when analysing their counterparts in drip irrigation, where only 2 % and 4.48 % of the DMUs have obtained the maximum efficiency score, with average technical efficiencies of 1.878 and 1.794 in citrus and persimmon. A great disparity is therefore confirmed between the different irrigation techniques, with differences of more than 40 %, where there are also great contrasts within each group. This indicator shows that while farms irrigated with traditional methods are very close to maximum efficiency, those irrigated with drip irrigation have much room for improvement. These inefficiencies may be due to the lack of experience and training of irrigators and technicians in irrigation management and other crop tasks that have been modified with the change to a relatively recent irrigation technique. This is not the case for surface irrigation, where users have a long and deep experience in irrigation management and associated cultivation techniques.

The efficiency of these four groups was compared by calculating the metafrontier (TE). As expected, the inefficiency achieved (excess over unity) has shot up compared to the individual frontiers, reaching 139.1 % in the case of the citrus area, where, in addition, 15 % of DMUs are completely efficient and the percentage is zero. Fig. 4 shows the differences between TE and TEK for each of the groups. The figure shows how for crops irrigated with traditional technologies, especially citrus, the difference between TE and TEK are much higher than for crops irrigated with drip irrigation. This indicates that although the group efficiency of flood irrigated plots is high, as shown above, efficiencies with respect to the metafrontier are low in traditional irrigation.

This can be explained by the results obtained for technological gap ratios (TGR^{K}) represent the state of the technology and show the efficiencies achieved with each of them. As can be seen in table x, the values corresponding to drip irrigation are significantly lower than the surface area, compared to 1.005 and 1.067 for drip citrus and persimmon, values of 1100 and 1717 are obtained for the surface area of persimmon and citrus, respectively. Drip citrus in particular reaches the minimum value, i.e. unity, in almost all observations, except in 10 of them with a deviation of only 0.05. These results, although with a larger deviation, are repeated in the drip of persimmons. This implies that with the inputs used this form of irrigation is obtaining the maximum possible income, they are operating at their potential. In contrast, surface irrigation has

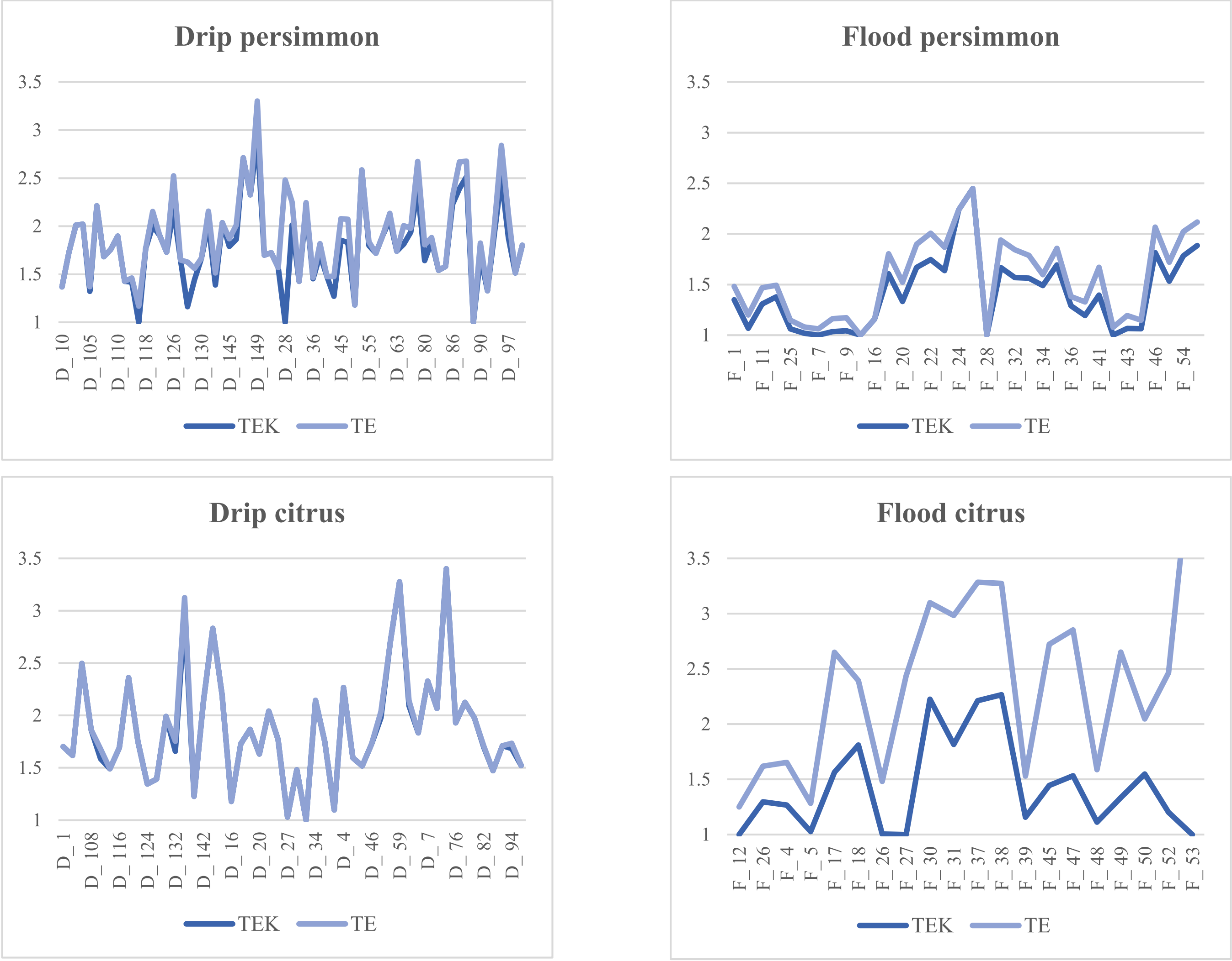

Fig. 4. Group-k (TE^{K}) and metafrontier (TE) of the irrigation communities grouped in four technologies.

room for improvement, which in the case of citrus reaches 71.7 % ($TGR^{K} = 1.717$) and in persimmon 10 % ($TGR^{K} = 1.100$). It is not surprising that drip irrigation is more efficient when considering the technology gap. According to the opinions of the experts interviewed, cultivation costs for entities using drip irrigation are lower. Although, as noted, irrigation costs are higher due to the energy cost of pressurized irrigation—despite using less water—the overall cultivation costs are lower in all cases. Centralized fertilization is less expensive than individual fertilization on surface-irrigated plots. Additionally, herbicide treatment costs are lower on drip-irrigated plots. The improvement in efficiency could also be a result of increased income per unit area, due to higher quality and quantity of yields from farms using pressurized irrigation. This is because the amount of water and fertilizer applied is more controlled, and applications occur at the most appropriate times. However, the experts interviewed did not reach a conclusive opinion on this matter.

The selection of the irrigation method is vital in the task of achieving sustainability in the sector. It is determinant to achieve not only cost savings, but also to avoid overuse of resources (Hoseini, 2019). This study highlights the urgency of introducing effective changes in all irrigation systems, in need of higher levels of productivity to achieve internationally competitive and sustainable agriculture. But in addition, irrigation techniques must be subjected to a thorough control of their performance, as these are processes that modify the water balance at the basin scale, and can reduce the available resources (Grafton et al., 2018; Hill and Walter, 2020).

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5. Conclusions

Although in recent years there has been a proliferation of studies on the consequences of the adoption of irrigation saving techniques, there are not many articles that study the effects on the economy of irrigators and, therefore, on the profitability of farms. In this paper we have compared the economic efficiency of different irrigation techniques in farms of the Spanish fruit sector in two stages.

In the first stage, it is concluded that there is a great variability in the costs of cultivation, since they are highly dependent on the farmers' choices. In general, it is observed that drip irrigation farms have lower costs. Despite this, professional farmers tend to prefer traditional irrigation because they can save costs by doing some tasks themselves, which in the case of drip irrigation is done by the IC. There is also great variability in income, which in many cases depends on factors beyond the farmer's control, such as the evolution of agricultural markets. Although costs are lower in the case of drip irrigation, for non-professional farmers (part-time and retired), who are the majority in the area, comfort is still the main advantage of the change of technique, i.e., they do not make the change for economic reasons. These different strategies followed by full-time and part-time farmers are not extrapolatable to other Spanish regions, where professional farmers prefer drip irrigation with a high degree of technification (Alcon et al., 2017).

In the second stage, efficiency is evaluated using metafrontiers, which makes it possible to distinguish between the most appropriate technology, which is undoubtedly drip irrigation, and inefficiencies due to poor management within each group, where it is observed that in drip irrigated crops there is much room for improvement. What are the factors that explain this low efficiency? Firstly, in the study area, the engineering companies in charge of building the drip networks designed and implemented standardised infrastructures without properly considering the complexities of local irrigation systems and farming traditions, which made collective irrigation management difficult and forced some ICs to make additional investments to adapt the parachuted technology through *bricolage* works (Poblador et al., 2021), as it has happened in other world regions (Benouniche et al., 2014; Glover et al., 2017). Second, because many farmers did not receive the necessary training to handle the new technologies, which in some cases resulted in inadequate management of these facilities with implications for water use and cost. In fact, farmers in the region are calling on the administration to provide specific training courses (Sanchis-Ibor et al., 2021), in subjects ranging from irrigation network management to business training, in order to improve the economic performance of their farms or ICs. Similar educational measures have been tested and recommended in the USA (Mpanga and Idowu, 2021). Other measures demanded by farmers and, to a large extent, recently taken up by the regional government in the Valencian Irrigation Strategy (GVA, 2021), include the need to renovate drip irrigation infrastructures that are becoming obsolete, as well as the massive introduction of photovoltaic energy to reduce irrigation pressurisation costs -successfully developed in other contexts (Carrillo-Cobo et al., 2014).

Additionally, it should be borne in mind that the study was carried out in an area with unique agricultural structural characteristics. There are great differences between different agricultural areas with local characteristics, hydraulic systems and water management, and this means that the results cannot be generalized. It is also important to appreciate that, as indicated by Pérez-Blanco et al. (2021), changes in irrigation techniques can cause externalities that must be taken into account, especially when the environment is affected (Hellegers et al., 2022, Sanchis-Ibor et al., 2024). Among these externalities, the most important is the effect on water consumption, which has not been addressed in this study. Aditionally, the introduction of other variables such as crop yields, labour costs would improve the applicability of the study.

For all these reasons, further progress must be made in the study of the economic, environmental and social effects of the change of technique, not only for users at farm level, but also for rural communities at the level of irrigable areas, or at the more general level of river basins, etc. The subsidy policies for irrigation modernization must consider these factors and scales. Including, in addition to investments in irrigation and energy infrastructure and technologies, a range of measures to improve farmers' skills in order to ensure the sustainable development of irrigated agriculture.

CRediT authorship contribution statement

Marta García-Mollá: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Carles Sanchis-Ibor:** Writing – review & editing, Validation, Conceptualization. **Virgina Vega-Carrero:** Writing – original draft, Methodology, Data curation. **Rosa Puertas Medina:** Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Marta Garcia-Molla reports financial support was provided by Polytechnic University of Valencia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgments

This work has been carried out in the framework of the IrriGo project funded by the Spanish State Research Agency PID2023-148676OB-C21 and by the PAID-11–23 of the Vice-Rectorate for Research of the Universitat Politècnica de València (UPV).

Data availability

The authors do not have permission to share data.

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