Irrigation and Drainage

WILEY

REVIEW ARTICLE

Evaluation of Performance in Collective Irrigation Agencies: A Systematic Review and a Meta-Analysis

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Received: 2 March 2025 | **Revised:** 25 October 2025 | **Accepted:** 26 October 2025

Keywords: benchmarking | crop irrigation | irrigation system | performance indicators | water resources management

Mots-clés: indicateurs de performance | analyse comparative | système d'irrigation | gestion des ressources en eau | irrigation des cultures

ABSTRACT

This study has carried out a comprehensive review of 51 studies using the original set of performance indicators (PIs) proposed by Malano and Burton in 2001, in order to evaluate the performance of collective irrigation agencies (CIAs) on a global scale. Bibliographic analysis has revealed a concentration of papers in semi-arid areas, especially in Spain and Turkey. The meta-analysis allowed a comprehensive diagnosis of CIAs operating in four countries (Italy, Malaysia, Spain and Turkey). The good performance of the CIAs was clearly associated with the following factors: satisfactory coverage of irrigation services, water delivery efficiency, financial self-sufficiency, capacity of fee collection and economic production. These factors included responses to smaller command areas, the prevalence of on-demand water distribution methods and water-conveying systems in pressured pipelines, and the significant presence of farm drip systems. In contrast, the poorly performing CIAs presented poor irrigation service coverage and an excessive water supply to crops and personnel staff. These issues led to insufficient system operations as well as to poor economic performance, due to low financial self-sufficiency, capacity of fee collection, economic production and high maintenance, operation and management costs.

RÉSUMÉ

Cette étude a consisté à passer en revue 51 études en utilisant l'ensemble original d'indicateurs de performance (IP) proposé par Malano et Burton en 2001, afin d'évaluer les performances des agences d'irrigation collectives (AIC) à l'échelle mondiale. L'analyse bibliographique a révélé une concentration d'articles dans les zones semi-arides, notamment en Espagne et en Turquie. La méta-analyse pour un diagnostic complet des AIC opérant dans quatre pays (Italie, Malaisie, Espagne et Turquie) a montré que les bonnes performances étaient clairement associées à une couverture satisfaisante du service d'irrigation, à l'efficacité de la distribution de l'eau, à l'autosuffisance financière, à la capacité de collecte des redevances et à la production économique en réponse à des zones de commande plus petites, à la prévalence des méthodes de distribution d'eau à la demande et du transport de l'eau dans des canalisations sous pression, et à la présence significative de systèmes de goutte à goutte dans les exploitations. En revanche, les AIC peu performantes ont montré une faible couverture des services d'irrigation, un approvisionnement en eau

Article title in French: Évaluation des performances des agences d'irrigation collective: une revue systématique et une méta-analyse.

excessif des cultures et du personnel conduisant à un fonctionnement insuffisant du système ainsi qu'une mauvaise performance économique due à faibles autosuffisance financière, capacité de collecte des frais, de la production économique et des coûts élevés d'entretien et d'exploitation et de gestion.

1 | Introduction

Irrigation management in the agricultural sector, the world's largest consumer of water (Foley et al. 2020), is highly inefficient (Samani and Jamshidi 2017; Biswas et al. 2021). This will lead to severe competition with other productive sectors in the water crisis, which will be humanity's greatest challenge in the 21st century (Connor 2015). Therefore, sustainable management of water resources and an increase in water use efficiency in the agricultural sector are essential to maintain and increase food security for current and future generations (Serageldin 2001; Wahaj et al. 2007; Javadinejad et al. 2019).

Collective irrigation agencies (CIAs), such as the Water User Associations, have emerged as prominent players in sustainable water use in irrigated agriculture on a global scale (Kazbekov et al. 2009; Wang et al. 2013). CIAs are non-profit organisations formed by a group of water users, such as ordinary land farmers, individual members of tenant farms, etc., to operate irrigation facilities, perform repairs, support maintenance costs and achieve equitable distribution of water (Abdullaev et al. 2010; Aarnoudse et al. 2018). These local associations pool and share financial, material, technical and human resources to manage irrigation and drainage systems in their jurisdiction to benefit all members (Roldán-Cañas and Moreno-Pérez 2021). This leads to more sustainable use of water in the agricultural sector and enhances the productivity of agricultural factors (Arslan et al. 2024).

The primary goals of the CIA are to provide an efficient supply and timely distribution of sufficient irrigation water to potential members (Vermillion 1999; Vafaei et al. 2021) through the collaborative participation of farmers in the management of the irrigation plan (Salman et al. 2008). This enables the technical and financial management of organisations (Vermillion 1999; Zema et al. 2018a) through long-term solutions for managing common resources through collective actions.

In several countries, CIAs suffer from problems related to both technical and financial aspects, for example, low irrigation efficiency and uniformity (Nam et al. 2016; Zema et al. 2019), high management costs and insufficient cost recovery (Zema et al. 2018a; Arslan et al. 2023). The poor performance of CIAs is due mainly to unsuitable water network operation, structural constraints, maintenance deficiencies and fee evasion. These factors negatively affect the overall functioning of CIAs and make users unsatisfied with collective irrigation services (Malano and Burton 2001; Koç 2007). The large number and complexity of these factors make the identification of critical issues for poor-performing CIAs a difficult task for technicians and accountants (Malano and Burton 2001). Owing to the lack of suitable and efficient diagnostic tools, the evaluation of the technical and economic performance of collective irrigation organisations is often neglected by CIA managers. This also occurs because the CIA's performance evaluation is considered a time-consuming and expensive activity, whose results are appreciable only in the long term (Malano et al. 2004).

In contrast, monitoring and evaluating the technical and economic performance of a CIA is an essential activity for improving collective irrigation management (Biswas 1984; Córcoles et al. 2012). Owing to this activity, it is possible to know to what extent the goals of the system are met and how efficiently the available resources are used (Plusquellec et al. 1990). Through performance monitoring, CIA managers and other stakeholders can identify weaknesses and areas for performance improvement and, as a consequence, make informed decisions (Alcon et al. 2017). Monitoring techniques are also useful for identifying the most suitable water management policies and the differences in the management types among CIAs and for measuring the effects of modernisation of irrigation management (Degirmenci et al. 2003; Tanriverdi et al. 2011; Soto-García et al. 2013).

In recent decades, several studies have proposed a set of monitoring and evaluation techniques for the collective management of water resources in agriculture, commonly known as 'benchmarking techniques'. As a result, there is now a substantial body of evaluation tools that present both opportunities and challenges for assessing CIA performance (Cakmak et al. 2004; Yercan et al. 2009; Zema et al. 2020). In general, CIA benchmarking uses statistical techniques to compare and describe CIA management as well as to identify critical issues and best management practices. Examples of these statistical techniques include principal component analysis (PCA), agglomerative hierarchical clustering analysis and data envelopment analysis (e.g., Rodrìguez-Dìaz et al. 2004; Córcoles et al. 2010, 2012; Zema et al. 2018a). The input data required by benchmarking techniques are a set of 'performance indicators' (PIs), which are related to the environment, financial, service delivery performance and productive efficiency of CIAs (Rodrìguez-Dìaz et al. 2004). A PI is simply a ratio relating at least two variables linked to a specific CIA performance (i.e., irrigated areas, irrigation water, management costs, staff units), thus reducing a large amount of information to a single number (Rodríguez-Díaz et al. 2008).

The set of benchmarking indicators proposed by Malano and Burton (2001), together with the methodology for their application, was the first and most commonly used scheme in the field of collective irrigation. This set has been accepted by several organisations, such as the FAO, the International Commission on Irrigation and Drainage (ICID), and the World Bank (Rodrìguez-Dìaz et al. 2004; Córcoles et al. 2010). Its wide acceptance and applicability have made this dataset a standard for evaluating the performance of CIAs worldwide. Data processing via PIs displays an organisation's position compared with its competitors ('external benchmarking') or analyses various organisation components over time to identify internal opportunities for improvement ('internal benchmarking') (Malano and Burton 2001; Rodrìguez-Dìaz et al. 2004; Arslan et al. 2023). Since its first appearance, the set of Malano and Burton's indicators has been used for CIA benchmarking in several countries, including Turkey (Cakmak et al. 2004; Yercan et al. 2009), Spain (Rodrìguez-Dìaz et al. 2004; Rodríguez Díaz et al. 2011; Córcoles et al. 2012), Italy (Zema et al. 2015, 2018a), India (Phadnis and Kulshrestha 2013) and Malaysia (Ghazalli 2004). Moreover, several studies have proposed replacements, integrations or modifications in the original set. In these applications, the PIs have become several dozen, and, obviously, some of those indicators may overlap or be challenging to calculate (Bertule and Miljøprogram 2017). Therefore, there is a need for a systematic analysis of past studies using the evaluation scheme of Malano and Burton, indicating how these indicators have been applied and whether these tools have been effective in exploring the diverse domains of CIA performance. In this context, a bibliographic analysis can offer valuable insights into the trends and patterns of research related to these aims.

Furthermore, a comparison of the technical and economic performance of CIAs identified through a meta-analysis based on comprehensive bibliographic research could provide indications of reciprocal relationships among PIs and the mean values across different agro-systems. By combining this global knowledge, it would be possible to pinpoint current patterns, prospective overlaps, and research gaps in the current literature. Surprisingly, despite the paramount importance of the collective irrigation sector on a global scale, no systematic reviews or meta-analyses have been performed to date, at least to the best of the authors' knowledge.

To fill this research gap, this study has carried out a systematic review of studies using the original set of PIs proposed by Malano and Burton and/or proposed derived indicators to benchmark the financial and technical performance of CIAs on a global scale. The performance of the CIAs in the reviewed papers analysed via these indicators has been processed using a meta-analysis. The results provide a comprehensive diagnosis of the collective irrigation sector on a global scale and establish a robust, evidence-based foundation for future research and policy formulation. By consolidating and distilling the collective insights from numerous studies, we aim to enhance the objectivity, efficiency and comparability of CIA performance evaluations, thereby fostering sustainable water management practices.

2 | Materials and Methods

2.1 | Bibliographic Review

This systematic review was carried out in October 2024 according to the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) 2020 guidelines to ensure transparency and reproducibility. This protocol consisted of the following steps (Figure 1):

2.1.1 | Definition of Eligibility Criteria

Papers were included if they met the following criteria:

- Publication type: Peer-reviewed journal articles
- Language: English
- Publication period: 2001–2024
- Content relevance: PIs related to those proposed by Malano and Burton (2001) within the context of collective irrigation systems,

and excluded if:

- non–peer-reviewed (e.g., technical reports, M.Sc. or Ph.D. theses)
- not directly related to irrigation PIs or collective irrigation management.

2.1.2 | Selection of Information Sources

Owing to their broad coverage of scientific and engineering literature, the following electronic databases were adopted: Scopus, Web of Science and Google Scholar.

2.1.3 | Search Strategy

To maximise the coverage of relevant studies, combinations of specific and general keywords were used: "Water User Association" OR "collective irrigation" OR "irrigation performance" OR "performance indicators" OR "Malano and Burton (2001)". The search results were filtered by publication date (2001 to 2024). Moreover, the reference list of each included paper was also manually screened to identify other relevant studies.

2.1.4 | Selection Process

After removing two duplicates and two papers in other languages, this initial search yielded 83 records. Titles and abstracts were screened, and 32 records were excluded because of a lack of relevance to the study topics. The full texts of the remaining 51 articles were then assessed and included in the final database.

2.1.5 | Data Collection Process

Using a standardised form in Microsoft Excel, the following bibliometric data were independently extracted from the 51 included studies:

1) author
2) publishing journal
3) publication year

4a and 4b) country and region of the study area

5) climate (tropical, arid, semi-arid, temperate, ocean, continental, polar)

6a and 6b) number of analysed CIAs and WUAs

7) monitoring period (years)
8) number of analysed PIs

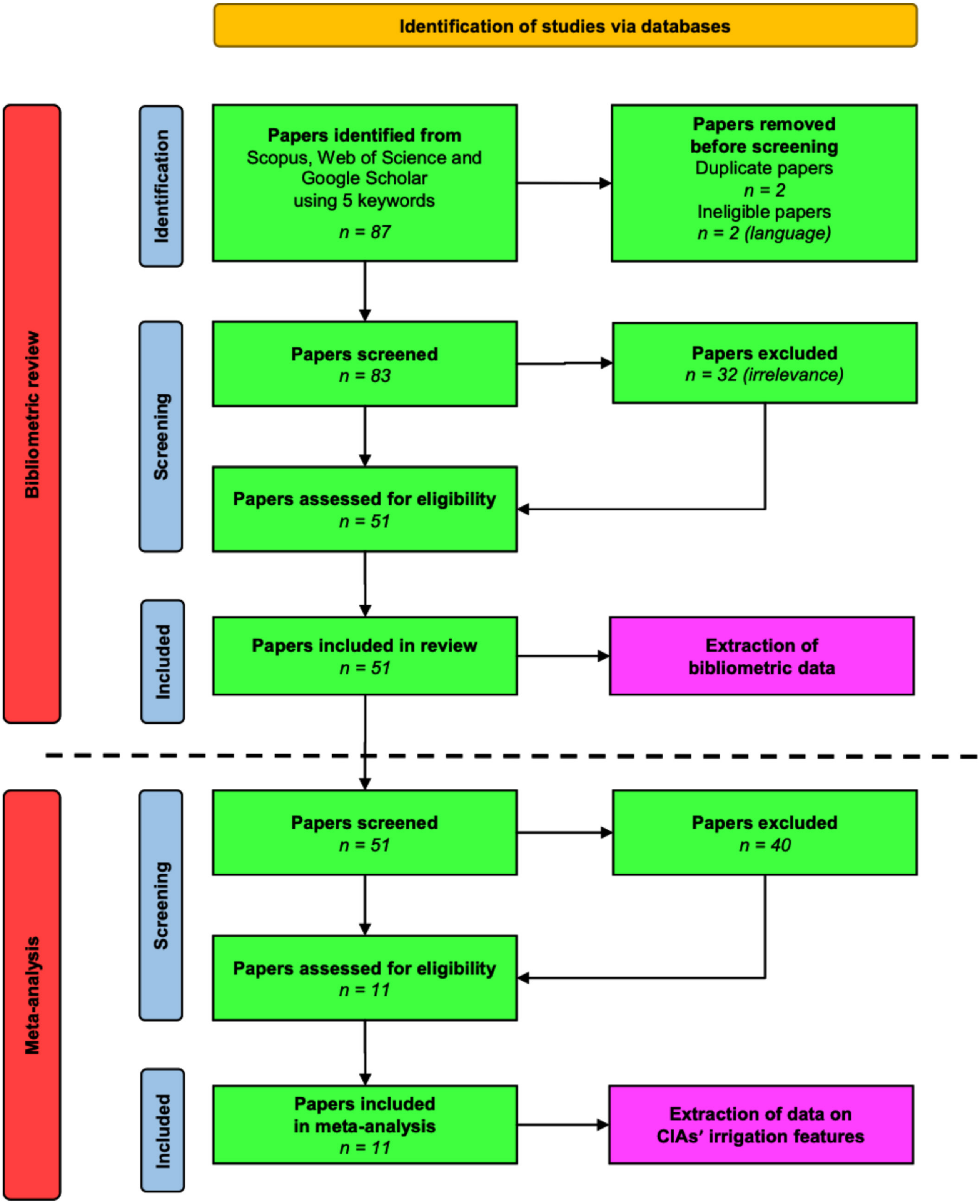


FIGURE 1 | Flow-chart of the PRISMA 2020 procedure adopted for the bibliographic review and meta-analysis.

9) method(s) for PIs processing

10a and 10b) citation counts (total number and number standardised per year of publication, equal to the ratio between the total number and the duration of the publication time from 2001 to present).

2.1.6 | Data Synthesis

The extracted data were tabulated and/or graphed to identify patterns in the application of PIs, geographic distributions, methodological approaches and citation impacts across studies.

2.2 | Meta-Analysis

2.2.1 | Data Collection and Organisation

The following 'irrigation features' related to the organisation and functioning of the CIAs were also derived from each paper (Table S1):

1. command area (in hectares)
2. management type (Water User Association, Cooperative, State company, mix of those types)
3. water conveying system (open channels, pressured pipeline, mix)
4. water network functioning (gravity, pumping, mix)
5. water resources (surface water, groundwater, drainage water, rainwater, wastewater, mix)
6. water resources availability (abundant, sufficient, insufficient)
7. farm irrigation system (surface, sprinkler, drip, mix)
8. water distribution (rotational, on-demand, mix).

Most of the 51 selected papers analysed more than one CIA, which in our study consists of one case study. Therefore, the number of analysed CIAs was 531, a number that is much higher compared to the selected papers. The analysis of these 'irrigation features' was limited to the 375 WUAs, which represent 70% of the sampled CIAs, to obtain homogeneous information.

In addition to the irrigation features, almost all the selected papers reported PIs. However, those papers that reported data about WUAs were subjected to further analysis to select studies reporting a minimum and representative dataset of PIs to allow the planned meta-analysis. Eleven papers out of the original 51 studies were selected according to the criteria reported in the following section, and the relevant values of the PIs were stored in a database (Figure 1).

2.2.2 | Data Processing Through Multivariate Statistical Analysis

First, a subset of 10 PIs out of the original dataset proposed by Malano and Burton (2001) was selected, following the indications of Arslan et al. (2023). This choice was carried out by selecting the minimum number of PIs that could cover all the areas associated with CIA organisation and management, that is, system operation, financial administration and productive efficiency. This choice is in line with Córcoles et al. (2010), who stated that it is possible to reduce the set of indicators by omitting only the production efficiency and environmental indicators without losing too much information. Moreover, the same authors have demonstrated that the indicators usually used in benchmarking irrigation performance have strong interrelations. Therefore, we reduce the number of PIs for analysis via a selection process. For example, we adopted the related PI, which was the ratio of a variable (e.g., management costs or production) by the irrigated area rather than referring it to the command area, irrigation water volume or crop yield. This choice is due to the high correlation between the irrigated and command area (ICR) and its strong association with the applied water or crop yield. The resulting indicators with the relevant calculation equations are reported in Table 1. Environmental indicators were not adopted since few CIAs carry out activities to measure and survey parameters related to irrigation water quality and use of fertilisers, and, therefore, the calculation of the environmental indicators was not possible (Arslan et al. 2023).

The values of PIs extracted from the selected 11 papers (Table S2) were subsequently homogenised via conversion to the same measuring unit for cross-comparisons. To identify each CIA, a code was used as follows. The first two letters of this code refer to the study country, the second letter and the two numbers after the dash are the initials of the paper author and the publication year, whereas the last number(s) refer(s) to the progressive numbering of the analysed CIAs. For instance, the code 'TR-A20-15' indicates the fifth CIA ('15') analysed by Arslan et al. (2020) ('A20') in Turkey ('TR').

The meta-analysis to compare the performances of the analysed CIAs was carried out via PCA and agglomerative hierarchical cluster analysis (AHCA) as multivariate statistical techniques. PCA was applied to reduce the dimensionality of the original dataset of 10 PIs, deriving the principal components (PCs). The latter are derivative and uncorrelated variables that are calculated as linear combinations of the PIs and explain at least 70% of the original variance. The variables, measured by different units, were first normalised, and the correlation matrix was computed on the basis of these normalised variables. Then, the eigenvalues and eigenvectors were calculated, and after the new derivative variables were sorted, four PCs were selected and retained. Finally, the data were projected onto the new subspace.

The AHCA was used to group the CIAs into homogeneous clusters according to the collective irrigation performance explained by the PIs. Ward's method was chosen as the clustering algorithm, and the Euclidean distance was used as a similarity–dissimilarity measure. WUA grouping through AHCA is reported in a dendrogram.

The statistical analysis, including PCA and AHCA, was carried out via XLSTAT software (release 2019.1). No artificial intelligence tools were used for any of the analyses.

3 | Results

3.1 | Bibliographic Analysis

Among the 51 selected articles, most are published in only four journals, accounting for 74% of the total number of papers: 'Agricultural Water Management' 27%, 'Irrigation and Drainage' 24%, 'Irrigation Science' 14% and 'Irrigation and Drainage Engineering' 9%. These papers are more concentrated in the period between 2006 and 2015, accounting for 58% of the total number, and the trend seems to have decreased in the last 10 years (Figure 2).

The reviewed papers received a mean number of citations equal to 52, with a maximum of 131, the latter recorded for the paper by Mateos (2008). When standardized to the number of publication

TABLE 1 | Performance indicators and relevant equations and meanings analysed in collective irrigation agencies (CIAs) in Italy, Spain and Turkey for the meta-analysis.

Indicator	Equation	Definition and meaning
Irrigated area/command area ratio (ICR, %)	IA/CA × 100	Ratio between the total annual irrigated crop area (IA) and the total command area (CA). It explains the size of the system (Zema et al. 2018b)
Irrigation water supply per unit Irrigated Area (IWSIA, m^3/ha-yr)	VIWS/IA	Ratio between the total volume of water supplied to water users for irrigation use over the year or season (VIWS) and IA. It is an indicator of water volume supplied to crops (Malano et al. 2004; Frija et al. 2009)
Main system water delivery efficiency (MSWDE, %)	VIWD/VIWS	Ratio between the total volume of irrigation delivery to water users for irrigation use (VIWD) and VIWS. It is an indicator of WUA efficiency in exploiting the water resources available for irrigation (Zema et al. 2015)
Relative irrigation water supply (RIS, %)	IWSIA/WIVR	Ratio between IWSIA and the water required by crops over the year or season (WIVR). It measures the degree of irrigation requirement fulfilment (Zema et al. 2018b)
Relative water supply (RWS, %)	WSIA/WIVR	Ratio of water supplied to an irrigation unit over a period (WSIA) and WIVR. It relates the water available for crops (including surface irrigation, groundwater pumped and rainfall) to the amount that crops need (Bos et al. 2005)
Total management, operation and maintenance (MOM) cost per unit Area (TMCIA, €/ha-yr)	MOMC/IA	Ratio between the total management, operation and maintenance cost of providing the irrigation and drainage service excluding capital expenditure and depreciation (MOMC) and IA. It standardises MOM costs standardised to the irrigated area (Zema et al. 2018b)
Revenue collection performance (RCP, %)	GRC/ GRI × 100	Ratio between the Gross revenues collected from payment of services by water users (GRC) and the Gross revenue due for collection from water users for the provision of irrigation and drainage services (GRI). It explains the CIA's capacity of due fee collecting (Koç 2007)
Staffing numbers per unit irrigated area (SUIA, persons/100 ha)	NPI/IA	Ratio between the total number of personnel employed in the provision of the irrigation and drainage service (NPI) and IA. It measures the personnel intensity per unit irrigated area (Yercan et al. 2009).
Cost recovery ratio (CRR, %)	GRC/ MOMC × 100	Ratio between GRC and MOMC. It is an index of the degree of financial self-sufficiency of the WUA (Zema et al. 2015)
Output per unit irrigated area (OUTIA, €/ha-yr)	TAVAP/IA	Ratio between the total value of agricultural production (TAVAP) and IA. It is an indicator of the unit production per unit of irrigated area (Rodríguez Díaz et al. 2011; Phadnis and Kulshrestha 2013)

years, the most cited paper was written by Nam et al. (2016) with 10.2 citations/yr. The most recent papers, published in 2024, did not receive any citations (Table S1).

Seventy-eight percent of the studies were carried out in semi-arid areas (Figures 3 and 4), and 6% were from arid zones, while no papers were published in oceanic and continental areas. The investigations have been carried out in very few countries, such as Turkey (35%) and Spain (29%) (Figures 3 and 4).

The number of CIAs considered in the studies is low: 75% of the papers reported fewer than 10 CIAs, and in most cases, fewer than five agencies were studied (Figure 4). The number of PIs used for performance analysis is highly variable: 51% of the papers reported only one to five PIs, whereas 30% analysed more than 10 PIs. There were only two articles reporting more than 20 PIs (Figure 4), although the number of PIs considered in these studies was related only to technical, financial and productivity PIs. The monitoring period is generally short: 49% of the analysed papers reported less data collected throughout less than 3 years, whereas only 14% of the studies analysed CIAs for 10 years or more (Figure 4).

Forty-seven percent of the reviewed studies reported simple surveys of data, whereas 10% used benchmarking techniques to process the data. There are also 10% of the papers analysing data by multivariate statistical techniques, such as clustering techniques and PCA (Figure 5).

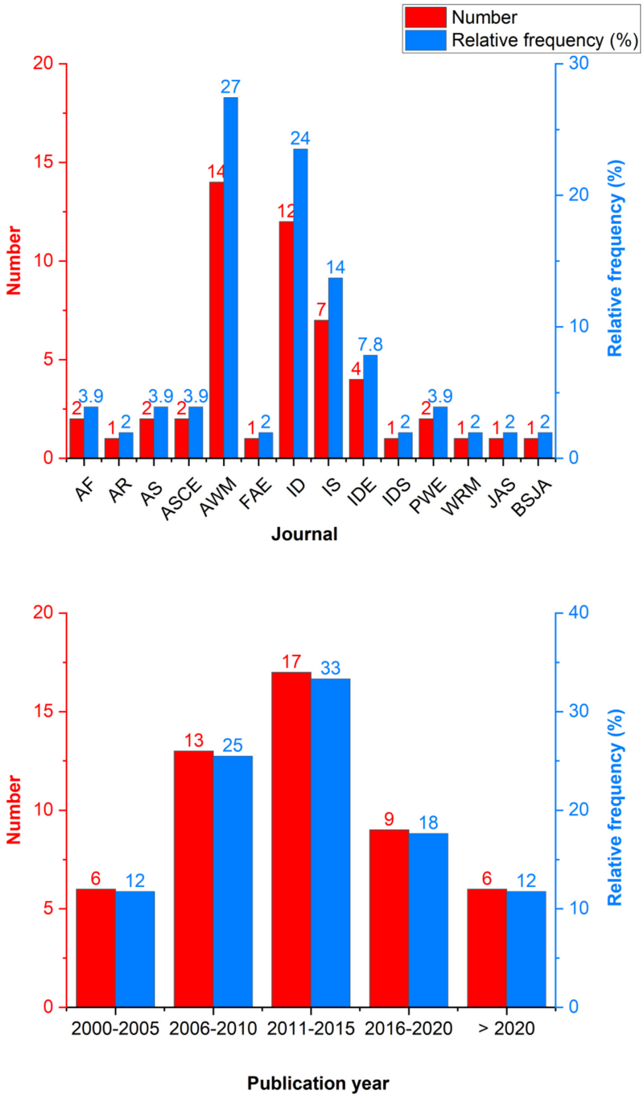


FIGURE 2 | Distribution of the 51 selected papers about performance indicators of collective irrigation agencies (CIAs) by publishing journal (upper) and publication year (lower). Legend: (Journals acronyms) AF = Turkish Journal of Agriculture and Forestry; AR = Agronomy Age Research; AS = Agricultural Systems; FAE = Food Agriculture and Environment; ID = Irrigation and Drainage; IDE = Irrigation and Drainage Engineering; IDS = Irrigation and Drainage System; IS = Irrigation Science; PWE = Paddy and Water Environment; WRM = Water Resource Management; AWM = Agricultural Water Management; ASCE = American Society of Civil Engineers.

3.2 | Analysis of Irrigation Features

In general, the 531 CIAs reported in the 51 papers are organised in the following main forms: water-user associations (WUAs) 70%, cooperatives 25% and state companies 5%. Specifically, with respect to WUAs, the command area is generally low, since 42% have an area lower than 20,000 ha, whereas fewer than 4% have a size greater than 30,000 ha. Surprisingly, the reviewed papers do not report the command area for 43% of CIAs (Figure 6).

The methods of water conveyance mainly use open channels (43% of cases), whereas only 27% transport irrigation water in pressured pipelines. A share of 9% conveys water by both open channels and pressured pipelines, whereas the method is not reported for 19% of the analysed WUAs. The method for water delivery is homogeneously distributed among gravity (23%), pumping (22%) and combination gravity–pumping (29%), whereas in 27% of agencies, this information is not reported (Figure 6).

A large variability in irrigation water resources is noticed, although for 30% of CIAs, these data are not reported. Forty-five percent of cases use surface water, 4% pump water from seepage for irrigation, while only 1% rely on wastewater, and 19% distribute water from more than one source. Approximately 35% of the analysed WUAs do not declare whether the water delivered to farmers is sufficient for crop irrigation. For CIAs in papers reporting this information, water is insufficient for 21%, sufficient for 37% and even abundant for 9% (Figure 6).

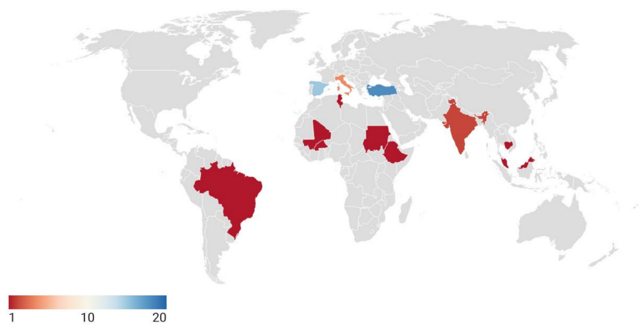


FIGURE 3 | Map showing the locations of the studies selected in this review for the bibliographic review and meta-analysis. The colours indicate the number of these studies.

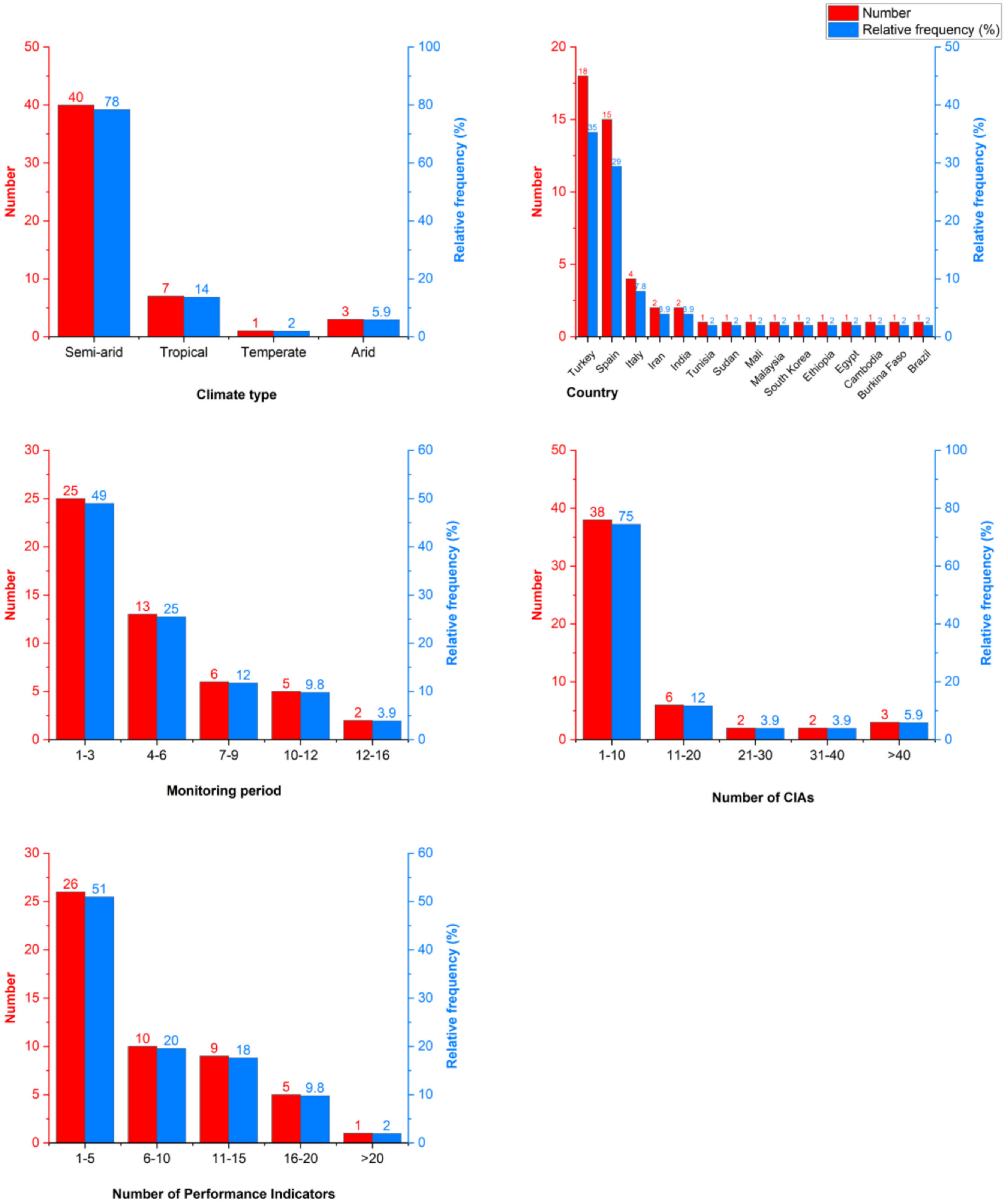


FIGURE 4 | Distribution of the 51 selected papers about performance indicators of collective irrigation agencies (CIAs) by climate type, country, duration of the monitoring period and number of analysed collective irrigation agencies and performance indicators.

There are many irrigation systems used in WUAs, although in 40% of the analysed cases, this information is not available. Specifically, 9% of WUAs use sprinkler irrigation, 10% drip irrigation, and 20% use both of these systems. For 20% of WUAs, surface systems are adopted, often in combination with other systems. Water is mainly distributed to farmers via rotational methods (31%), whereas on-demand distribution occurs for 18% of WUAs (5% in combination with rotation). However, for

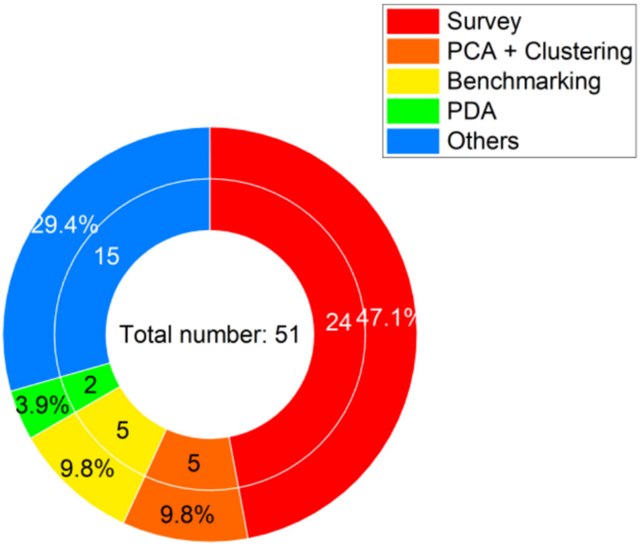


FIGURE 5 | Distribution (relative frequency in percent) of the data processing methods used in a total number of 51 papers selected to analyse the performance indicators of collective irrigation agencies (CIAs) (data in percentage of the total number of cases, equal to 61, since in some papers, more than one method was used). *Note: PDA = panel data analysis.*

47% of the analysed cases, this information was not available (Figure 6).

3.3 | Meta-Analysis of PIs in Selected WUAs

Surprisingly, very low coefficients of correlation were found between pairs of PIs (Table 2), except for RIS, which was well correlated with RWS (r = 0.8).

The PCA provided four PCs that cumulatively explained 71% of the total variance of the original PIs. ICR, IWSIA, RIS and RWS have high loadings on the first PC, whereas SUIA, MSWDE and OUTIA significantly weigh on PC2. Moreover, PC3 is strongly associated with the RCP and CRR. Only TMCIA is weighted on the fourth PC. All these loadings are positive, except for the loading of ICR on PC1 (Table 3 and Figure 7a).

Considering these loadings, PCA coupled with AHC grouped the analysed CIAs into three clusters (Figure 7a,b). Turkish and Italian agencies are prevalent in the first and second clusters, whereas Spanish agencies are more abundant in the third group (Figures 7b and 8).

When the values of the analysed PIs are averaged among the CIAs composing each cluster, three levels of performance can be discriminated. The CIAs of Cluster #3 show the best values for almost all PIs, except SUIA, IWSIA and TMCIA. In contrast, the CIAs of Clusters #1 and #2 are, in general, characterised by the worst values of PIs that are related to system operation (Cluster #2) and financial and productive (Cluster #1) performance. Only SUIA and IWSIA (Cluster #1) and TMCIA (Cluster #2) show the most satisfactory performance among the clusters (Table 4).

All CIAs in Clusters #1 and #2 are WUAs. All CIAs supply enough water to crops, but irrigation water is insufficient in some CIAs of Cluster #1, and surface irrigation resources are commonly adopted in CIAs in Clusters #1 and #3, at 56%–58%. The latter percentage decreases to 43% in Cluster #2, whereas another 48% is a combination of irrigation water from different sources. It is also worth noticing that, in Cluster #3, (1) CA is the lowest among the size classes, since 47% of CIAs cover less than 1000 ha; (2) 50% of CIAs use sprinklers as prevalent farm irrigation systems; (3) 58% distribute water mainly on demand; (4) the water functioning system is mainly by pressure (63%); and (5) the percentage of pressured pipelines is not negligible, being equal to 21%. In contrast, the CIAs in the other clusters show predominantly medium-sized command areas, with over 65% of the farms covering CAs between 1000 and 10,000 ha. Mixed farm irrigation systems are generally used, ranging from 44% to 57%, and irrigation water is delivered by rotational methods on average in 66% of CIAs, with a peak of 87% in Cluster #2. Water is commonly conveyed in open channels (> 98%) and by gravity (> 83%) (Figure 9).

4 | Discussion

4.1 | Bibliographic Analysis

Bibliographic analysis revealed that 'Agricultural Water Management' published more than one-fourth of the 51 reviewed papers. This is presumably due to the eminence of this journal, which specifically addresses agricultural water and has the highest impact factor among this journal category (6.611). Another 47% were published in 'Irrigation and Drainage', 'Irrigation and Drainage Engineering' and 'Irrigation Science', all of which are specialised journals. This means that the interest of academics lies in journals that expressly focus on the irrigation sector. It is important to notice that a peak in papers published between 2006 and 2015 is expected since the paper of Malano and Burton was dated in 2001. However, the general trend of papers focusing on the evaluation of collective irrigation performance through PIs has noticeably slowed during the past 10 years, which raises the possibility that interest in this field of study has decreased.

The fact that more than 60% of the reviewed studies are concentrated in Turkey and Spain may be due to two factors. First, the importance of irrigation concerns in Spain, which is one of the most developed agricultural sectors in Europe, but suffers from a chronic scarcity of irrigation water due to arid to semi-arid climatic conditions (Berbel et al. 2019). Second, there is a long history and importance of collective irrigation in Turkey, which has several ancient waterworks dating back 4000 years, some of which are still in operation after several centuries or even several millennia (Öziş 2015). The limited availability of irrigation water as well as the competition among the different productive sectors for water usage may also be a reason for the high concentration of studies in semi-arid areas. Surprisingly, very little attention has been given to collective irrigation in arid zones. Presumably, in these areas, collective irrigation does not play a key role in water resource management in agriculture since irrigation is practised mainly at the farm level and/or exploits local water resources (Roldán-Cañas and Moreno-Pérez 2021).

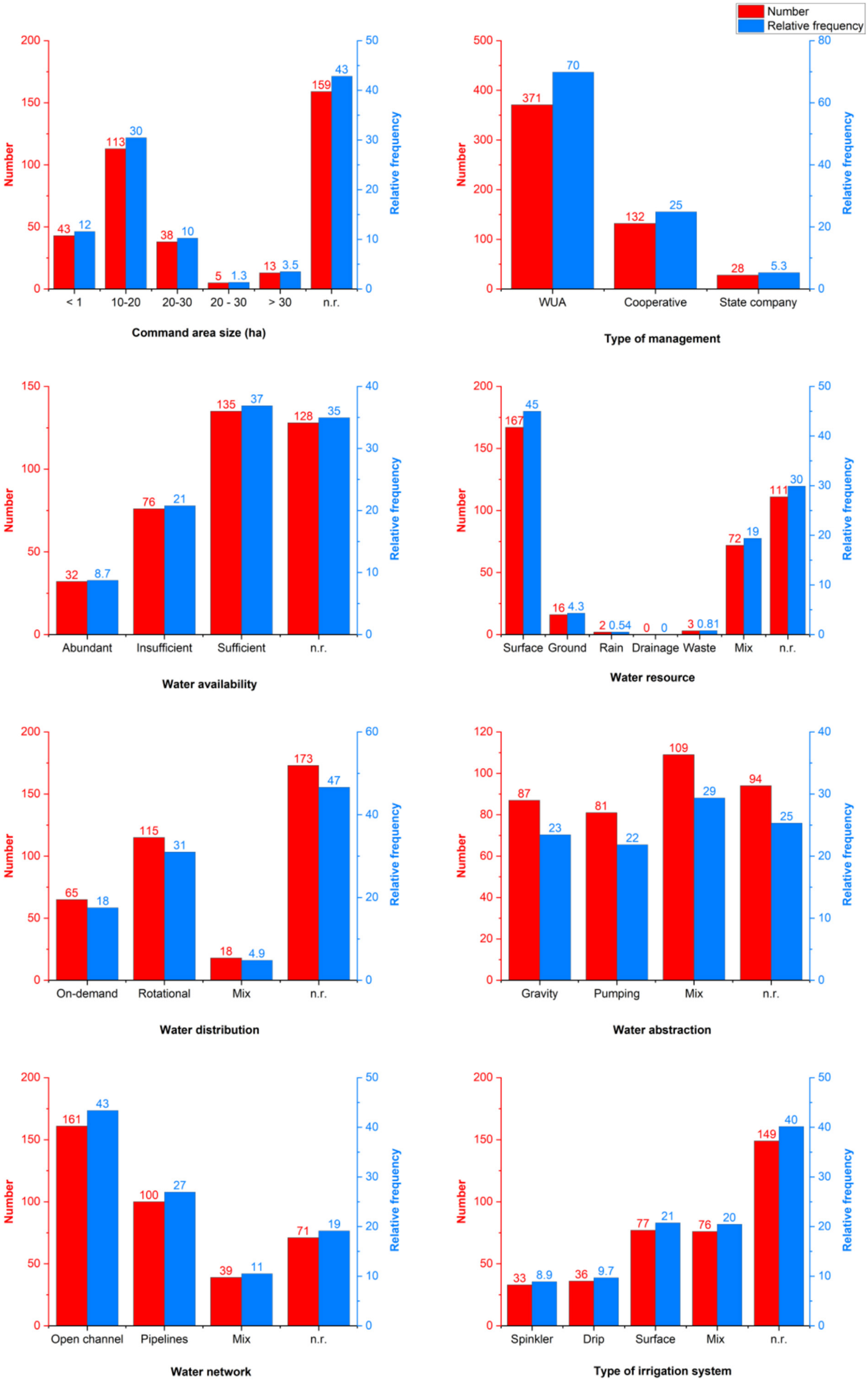


FIGURE 6 | Distribution of the 531 analysed collective irrigation agencies (CIAs) per feature of the system.

TABLE 2 | Correlation matrix between pairs of performance indicators of collective irrigation agencies (CIAs) analysed in the selected 11 papers.

Performance indicators	*ICR*	*SUIA*	*IWSIA*	*MSWDE*	*RIS*	*RWS*	*RCP*	*CRR*	*TMCIA*	*OUTIA*
ICR	**1**	−0.33	−0.15	0.14	−0.40	−0.38	0.17	0.47	−0.20	−0.07
SUIA		**1**	−0.10	0.31	0.36	0.21	0.04	−0.21	0.08	0.46
IWSIA			**1**	−0.31	0.36	0.29	−0.11	−0.08	−0.05	−0.07
MSWDE				**1**	−0.001	−0.39	−0.03	0.08	0.18	0.30
RIS					**1**	**0.80**	0.03	−0.17	0.004	0.03
RWS						**1**	0.006	−0.18	−0.10	−0.04
RCP							**1**	0.43	0.16	0.22
CRR								**1**	−0.12	0.13
TMCIA									**1**	0.15
OUTIA										**1**

Note: Values in bold are different from zero with a significance level of 0.05; the meaning of acronyms is reported in the nomenclature.

TABLE 3 | Loadings of performance indicators of collective irrigation agencies (CIAs) analysed in the selected 11 papers on the four principal components (PC) of principal component analysis.

	Principal components			
Performance indicators	**PC1 (26%)**	**PC2 (20%)**	**PC3 (15%)**	**PC4 (10%)**
ICR	**−0.72**	−0.18	0.28	−0.25
SUIA	0.41	**0.72**	−0.02	−0.28
IWSIA	**0.46**	−0.37	0.22	0.09
MSWDE	−0.29	**0.68**	−0.21	−0.26
RIS	**0.82**	0.12	0.32	−0.13
RWS	**0.82**	−0.14	0.37	−0.08
RCP	−0.20	0.27	**0.73**	0.36
CRR	−0.52	0.01	**0.69**	−0.08
TMCIA	0.03	0.42	−0.16	**0.81**
OUTIA	−0.003	**0.73**	0.22	−0.09

Note: The meaning of acronyms is reported in the nomenclature; data in parentheses are the percentage of total variance in the original variables explained by each PC; the numbers in brackets highlight the highest loadings; bold characters indicate the highest loading among the retained PCs.

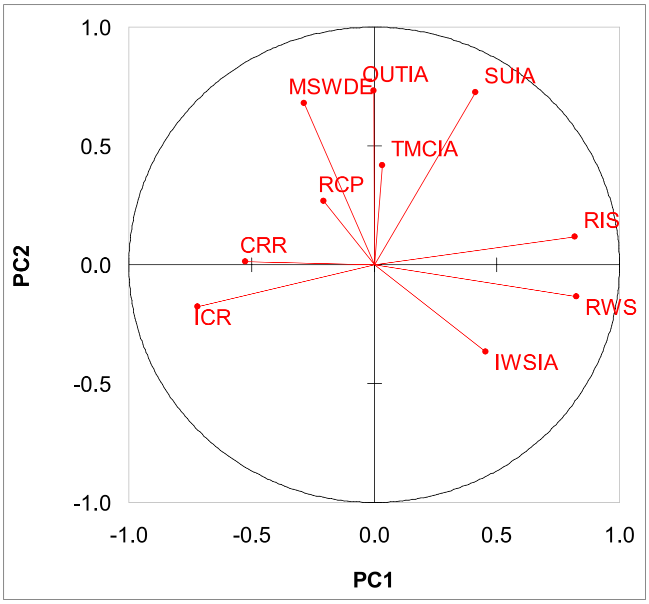
The absence of studies in oceanic and continental areas may be explained by the minor role of irrigation in relation to sufficient rainwater input feeding crops (Döll and Siebert 2002; Nie et al. 2021).

Generally, the reviewed studies consider a small number of WUAs, which means that the attention mainly focuses on specific case studies, while the studies carried out at the regional or national scale are much less. Moreover, despite large variations in the number of PIs reported in the reviewed papers, the studies generally analyse a few aspects of collective irrigation performance, and even one to five PIs are used in the majority of publications. The overall management of CIAs was carried out in only 10% of the papers, which analysed more than 15–20 PIs, and only one study used more than 20 PIs. Additionally, the monitoring periods tend to be relatively short, with more than half of the studies covering less than 3 years. Moreover, the frequency of studies in the total number is exponentially decreasing with the duration of the monitoring period. This limited time scale of analysis may affect the generalisability of the findings and might not provide a comprehensive understanding of collective irrigation agency performance over the long term.

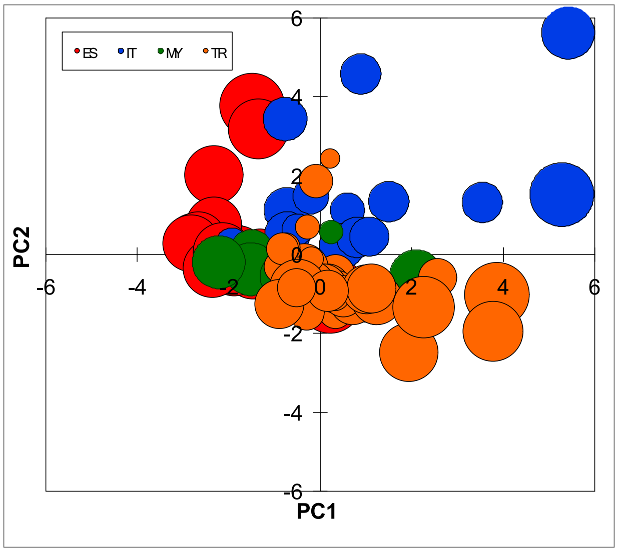
With respect to the methodological approach of the reviewed studies, the range of data processing methods is very large, but most investigations consist of mere data surveys. Despite the importance of monitoring activities for evaluating CIA's performance by a quantitative approach, simple data surveys do not properly valorise benchmarking techniques (Rodríguez-Díaz et al. 2008; Córcoles et al. 2012). These techniques show powerful analytical capacity, which can support the CIA's authorities in identifying the strengths and weaknesses of the associations and may improve their performance based on the planned objectives (Alcon et al. 2017; Arslan et al. 2023). The bibliographic analysis also revealed how a large fraction of studies analyse data via multivariate statistical techniques, such as clustering and PCA. This demonstrates that current innovative approaches are being applied to better understand CIAs' performance in an integrated and meaningful approach. Surprisingly, linear programming methods, such as data envelopment analysis (DEA), which are considered very effective at calculating the relative efficiencies of CIAs, have been used in only three studies. A broader application of DEA would allow the simultaneous analysis of several inputs and outputs to evaluate CIAs' efficiency ratings within a set of analysed units without the development of standards against which efficiency is measured (Malano et al. 2004; Zema et al. 2018a).

4.2 | Analysis of Irrigation Features

This systematic review has provided interesting information about the characteristics of collective irrigation agencies. First,

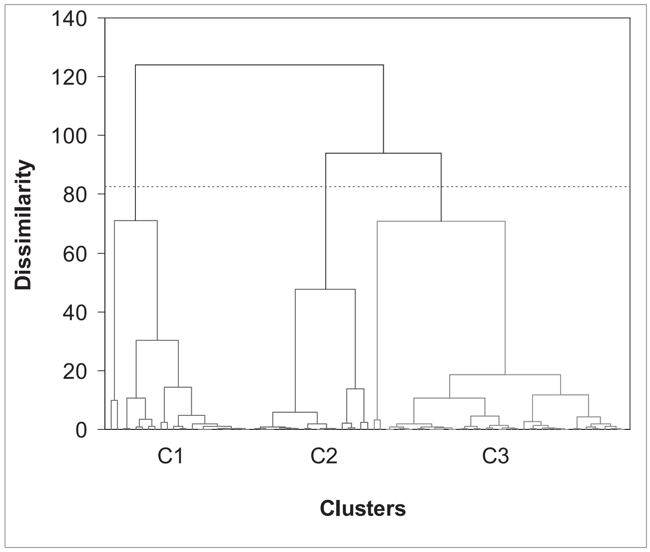


(a)



(b)

FIGURE 7 | Loadings (a) and bubble plot (b) of performance indicators of collective irrigation agencies (CIAs) analysed in the 11 selected papers on the four principal components (PCs) of principal component analysis. *Note:* The meaning of acronyms is reported in the nomenclature; the bubble size is proportional to the value of PC3.



(a)

Cluster		
C1	**C2**	**C3**
TR-A20-1	TR-A20-3	IT-Z18-7
TR-A20-2	TR-A20-5	IT-Z15-7
TR-A20-4	TR-A20-6	ES-C12-1
TR-A20-7	TR-A20-8	ES-C12-2
TR-A20-10	TR-A20-9	ES-C12-5
TR-A20-11	TR-A20-12	ES-C12-6
TR-A20-13	TR-A20-15	ES-RD11-1
TR-A20-14	TR-A20-17	ES-RD11-2
TR-A20-16	TR-A20-18	ES-RD11-3
TR-A20-20	TR-A20-19	TR-C10-6
TR-A20-21	TR-K19-1	ES-RD08-1
TR-A20-22	TR-K19-4	MY-G04-2
TR-K19-2	IT-Z18-8	MY-G04-3

FIGURE 8 | Dendrogram (a) and composition (b) of clusters of collective irrigation agencies (CIAs) analysed in the selected 11 papers, as provided by the agglomerative hierarchical cluster analysis (AHCA). *Note:* the red dashed line refers to the level of dissimilarity.

the command area of these agencies is generally low, which means that the collective irrigation service is often fractioned into several but small entities. Smaller CIAs, such as those in Turkey and Italy, may help managers better control administrative procedures and the structural conditions of water networks. However, CIAs with a large size may benefit from an economy of scale, as observed in some Spanish CIAs (Rodríguez-Díaz et al. 2008), allowing the division of MOM and staff costs among several hectares (Arslan et al. 2023).

Second, WUAs and cooperatives represent by far the prevalent management form of CIAs worldwide, showing that, in the collective irrigation sector, public action is in the minority. This depends on the fact that farmers are stimulated to self-sufficiently manage agricultural production (Vafaei et al. 2021).

Third, from an infrastructural point of view, water conveyance in open channels is common in approximately one-half of the analysed WUAs, and water pumping for both water supply from seepage and delivery to farms accounts for a significant share of the total sample of studies. The replacement of open channels with pressurised pipelines for water delivery may be a beneficial option for several CIAs. On the one hand, this replacement avoids water loss from evaporation or theft; on the other hand, it allows the conversion of potential energy into electricity by hydro-turbines or pumps-as-turbines with additional revenues for CIAs due to energy sales and clear environmental

TR-K19-3	IT-Z18-9	MY-G04-7
TR-K19-5	IT-Z18-10	ES-RD04-1
TR-K19-6	ES-C12-3	ES-RD04-2
TR-K19-7	ES-C12-4	ES-RD04-3
TR-K19-8	TR-C10-3	ES-RD04-4
IT-Z18-1	TR-C10-4	ES-RD04-5
IT-Z18-2	TR-C10-5	
IT-Z18-3	TR-C10-7	
IT-Z18-4	TR-C10-8	
IT-Z18-5	MY-G04-6	
IT-Z18-6		
IT-Z15-1		
IT-Z15-2		
IT-Z15-3		
IT-Z15-4		
IT-Z15-5		
IT-Z15-6		
TR-C10-1		
TR-C10-2		
ES-RD08-2		
MY-G04-1		
MY-G04-4		
MY-G04-5		
TR-C04-1		
TR-C04-2		
TR-C04-3		
TR-C04-4		
TR-C04-5		

(b)

FIGURE 8 | (Continued)

sustainability due to the production of renewable energy (Algieri et al. 2020; Belaud et al. 2020; Chacón et al. 2021). Pumping operations, in addition to requiring energy for water supply and/or delivery, represent an important cost for the entire financial budget of CIAs, as demonstrated by several studies with special reference to Spanish WUAs (Díaz et al. 2004; Córcoles et al. 2012; Alcon et al. 2017).

Fourth, it is worth noting that irrigation water sources are multiple, although a considerable percentage of agencies do not report their data. Surface water, alone or in combination with other water types, particularly groundwater, is the most commonly used source for irrigation. For more than one-third of the analysed CIAs, it is unclear whether the water delivered to farmers is sufficient for crop irrigation, which may raise questions about the efficiency of water management in these systems. The use of non-conventional water, such as drainage water or wastewater, is marginal. Research has demonstrated for many decades that irrigation with urban and agro-industrial wastewater is a safe and sustainable practice if proper application protocols are followed and if soil properties are carefully monitored (Barbera et al. 2013; Biswas et al. 2021; Singh 2021). Irrigation with wastewater allows the supply of organic matter and nutrients to crops and soils, and saves conventional water. This is desirable considering the expected reduction in water availability due to climate change effects (Pedrero et al. 2010; Kesari et al. 2021; Hoogendijk et al. 2023).

Fifth, at the farm level, the irrigation systems used in the analysed CIAs are equally distributed, but a slight prevalence of surface irrigation, that is, basin, furrow and border methods, is recorded. However, drip irrigation is far from widely used in the analysed WUAs, and this represents a concern, since, when possible, this system allows noticeable application efficiency with consequent water savings and reduced fees for farmers (Brouwer et al. 1988; Burt et al. 2000).

Sixth and finally, rotational irrigation is prevalent among water delivery methods, which leads to lower equity and dependability

TABLE 4 | Means and standard errors of the performance indicators in the clusters (C1, C2 and C3) of collective irrigation agencies analysed in the 11 selected papers, as revealed by AHCA.

Cluster	ICR (%)	SUIA (number 100 ha^{-1})	IWSIA (m^3 ha^{-1} yr.$^{-1}$)	MSWDE (%)	RIS (m^3 m^{-3})	RWS (m^3 m^{-3})	RCP (%)	CRR (%)	TMCIA (€ ha^{-1} yr.$^{-1}$)	OUTIA (€ ha^{-1} yr.$^{-1}$)
					Mean					
C1	50.3	1.04	8429	71.7	1.49	2.13	0.61	0.30	1813	5713
C2	35.0	1.72	18,380	44.0	3.37	5.43	0.70	0.37	828	7698
C3	80.3	1.53	8519	80.6	1.22	1.38	0.93	0.84	1570	23,514
					Standard error					
C1	4.20	0.18	545	3.44	0.12	0.16	0.03	0.03	893	826
C2	3.61	0.92	3070	5.80	0.54	0.43	0.04	0.05	260	2339
C3	5.30	0.79	1755	4.03	0.13	0.13	0.02	0.06	486	8383

Note: The meaning of acronyms is reported in the nomenclature.

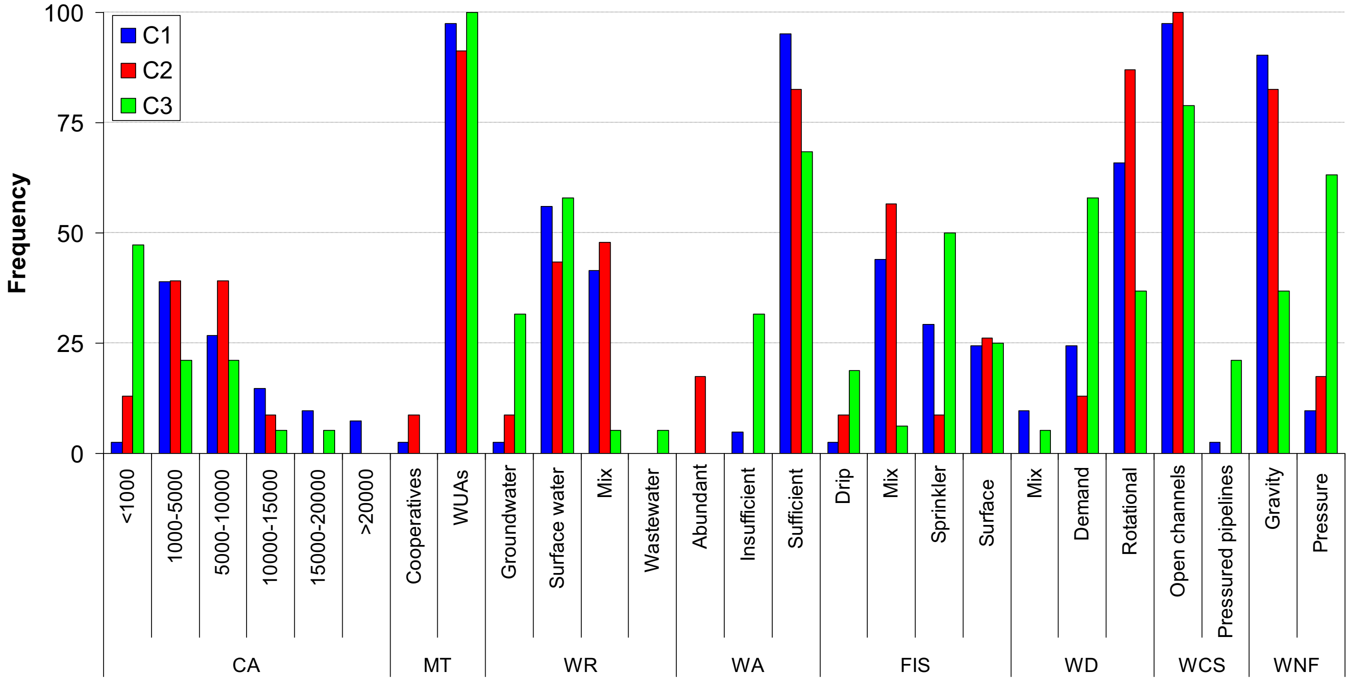


FIGURE 9 | Relative frequency of categories of irrigation features in the clusters (C1, C2 and C3) of collective irrigation agencies (CIAs) analysed in the 11 selected papers. *Note:* The meaning of acronyms is reported in the nomenclature; CA is expressed in ha.

of the collective service compared with on-demand delivery methods (Molden and Gates 1990; Molden et al. 2007). The conversion of rotational scheduling of irrigation to on-demand delivery is often long and expensive (Playán and Mateos 2006; Berbel et al. 2019). A good compromise may be 'limited rate arranged-demand' or 'semi-demand' water distribution methods (Merriam et al. 2007; Zema et al. 2019), in which the irrigator requests a specific volume of water and flow rate to be arranged with CIA management (Mateos et al. 2002).

4.3 | Meta-Analysis of PIs in Selected WUAs

In general, several authors report significant correlations among many PIs (e.g., Córcoles et al. 2010; Zema et al. 2015). However, the statistical analysis of the PIs surprisingly reveals low correlations between pairs of indicators. This might be attributed to the relatively low number of PIs used in this study and the large variability in the values of PIs, the latter being associated with the high number of case studies. The good correlation between RIS and RWS may be explained by the fact that higher rainfall may result in more water being supplied to crops.

Among the four PCs explaining most of the variance in the PIs measured in the analysed WUAs, the first is clearly related to the efficiency of the water delivery system. The third component is associated with the financial performance of WUAs, and PC4 depends on the MOM performance of the system.

The clustering algorithm revealed that, on the basis of these major components, CIAs are not grouped according to country, which shows that irrigation performance is more closely tied to the unique qualities of the irrigation agencies than to their geographical location.

The clusters grouping the analysed WUAs presented different levels of performance. The WUAs of the cluster grouping Spanish WUAs show higher system operation, financial and production levels. This good performance may be due to satisfactory irrigation service coverage, water delivery efficiency, financial self-sufficiency, and fee collection capacity, all of which are greater than 80%, with a peak of 90%. Even the economic production per unit of irrigated area is over 5 times greater than the mean value calculated for the other clusters. Several other factors may explain the better functioning of these WUAs compared with those in the other clusters. The smaller area of these WUAs allows better control of revenue collection performance and water system functioning, limiting fee evasion and out-of-service periods. Moreover, the prevalence of on-demand water distribution methods and pressured water functioning, along with the significant presence of farm drip systems, helps ensure good irrigation services in Spain (Rodríguez Díaz et al. 2011), allowing a reduction in water waste and feasible irrigation efficiency. Moreover, several WUAs in Spain are not-for-profit associations of users that manage water networks for supply and delivery, which allows a cost recovery close to 100% (Arslan et al. 2023).

The collective irrigation performance of the other two clusters, which include mainly Turkish and Italian WUAs, is affected by poor system operation or financial procedures and limited production yields. More specifically, the poor performance of the WUAs in one cluster is due to very low irrigation service coverage and excessive water supply to crops and personnel staff, although the MOM cost per unit area is lower. The latter result may be misleading since this low cost may be due to insufficient maintenance of the water networks. According to Koc et al. (2006), excessive water supply to crops and insufficient revenue collection severely influence the technical and financial management of Turkish WUAs (Cakmak et al. 2004; Uysal and Atış 2010). Moreover, the low use of water-saving farm irrigation systems, the prevalent rotational methods for water delivery and the high incidence of open channels and water network functioning by gravity may also be factors causing high water waste in these WUAs. Previous studies (Zema et al. 2015; Kartal et al. 2019) reported that, in Italy and Turkey, the RIS and RWS indicators far exceed 100%, with a peak of over 400%, which proves considerable waste of irrigation water.

The insufficient service of WUAs in the largest cluster may be explained by poor economic performance, namely, low financial self-sufficiency, the capacity for fee collection and economic production and high MOM costs. In these WUAs, the MOM costs are the highest, and the revenue collection performance, cost recovery ratio and economic production per unit irrigated area are the lowest among the three clusters. In this context, the situation of Italian WUAs is emblematic since the MOM costs are extremely high due to the oldness and poor conservation of the irrigation network (Zema et al. 2018a). The latter costs heavily affect overall economic performance, and a higher service level does not correspond to these high costs. It should be noted that part of these costs is supported by regional authorities, which do not stimulate careful and sustainable financial management. Moreover, both in Italy and Turkey, fee evasion is high, despite the recent improvement in the revenue collection procedure in Italian WUAs (Zema et al. 2018a). In line with Bos (1997) and Marre et al. (1997), the poor values of PIs in the WUAs of the largest cluster indicate that the level of acceptance of irrigation services by farmers is not optimal.

5 | Conclusions

Bibliographic analysis has revealed a concentration of papers evaluating the performance of CIAs in Spain and Turkey as well as in semi-arid areas, together with a decrease in studies in the last decade. Moreover, research has focused mainly on a few CIAs analysed throughout very short periods, generally using simple monitoring techniques.

The analysis of the irrigation features of the CIAs in the 51 reviewed studies revealed: (1) generally small command areas; (2) many case studies with water conveying systems by gravity in open channels and delivery by rotational methods; and (3) an equal distribution between sprinkler and surface irrigation systems at the farm level.

The meta-analysis of PIs reported in 11 selected papers with case studies in Italy, Spain, Turkey and Malaysia revealed that the good performance of WUAs was clearly associated with satisfactory irrigation service coverage, water delivery efficiency, financial self-sufficiency, fee collection capacity and economic production in response to smaller command areas; the prevalence of on-demand water distribution methods and water conveyance in pressured pipelines; and the significant presence of farm drip systems. In contrast, the poorly performing WUAs presented very low irrigation service coverage and excessive water supply to crops and personnel staff, all of which are factors leading to insufficient system operations as well as low financial self-sufficiency, fee collection capacity, economic production and high MOM costs.

Overall, this study lays the foundation for future research in this area, suggesting that researchers should consider a broader scope and use advanced analytical techniques to understand the complex dynamics of collective irrigation agency performance.

Nomenclature

AHCA	Agglomerative Hierarchical Cluster Analysis
CA	command area
CIA	collective irrigation agency
CRR	cost recovery ratio
ES	Spain
FIS	farm irrigation system
ICR	irrigated area/command area ratio
IT	Italy
IWSIA	annual irrigation water supply per unit irrigated area
MOM	management, operation and maintenance
MSWDE	water delivery capacity
MT	management type
MY	Malaysia
n.r.	not reported.
OUTIA	output per unit irrigated area
PCA	principal component analysis
PDA	panel data analysis
PI	performance indicator
RCP	revenue collection performance
RIS	annual relative irrigation supply
RWS	annual relative water supply
SUIA	staffing numbers per unit of IRRIGATED AREA
TMCIA	total management, operation and maintenance cost per unit irrigated area
TR	Turkey
WA	water availability
WCS	water conveying system
WD	water distribution
WNF	water network functioning
WR	water resources
WUA	water user association

Funding

This work was funded by the Next Generation EU - Italian NRRP, Mission 4, Component 2, Investment 1.5, call for the creation and strengthening of “Innovation Ecosystems”, building “Territorial R&D Leaders” (Directorial Decree n. 2021/3277) - Tech4youproject - Technologies for climate change adaptation and quality of life improvement, n. ECS0000009. This work reflects only the authors' views and opinions; neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Bibliographic information of the 51 selected papers about performance indicators of collective irrigation agencies (CIAs). *See the Excel file attached to the submission*. **Table S2:** Values of the performance indicators extracted from the 11 selected papers on the evaluation of performance in the water-user associations. *See the Excel file attached to the submission*.