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Review Article

Former and Current Trend in Subsurface Irrigation Systems

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ABSTRACT

The main purpose of this review is to find the diversity in research studies of subsurface irrigation systems in the past two decades. Two periods of five years were selected to reflect the research studies at the beginning and the end of the comparing periods range. A statistical sorting was used to investigate the distribution of papers according to objectives, types of irrigation systems, research methods, and limitations of the studies. Results showed that the measurements and evaluations were the most presented objectives of the selected papers for both periods. Furthermore, almost 90 percent of the recent papers used multiple research methods, unlike the papers published in the former period which only 56 percent of them used multiple methods. Also, more than 90 percent of the recent papers used a single irrigation system. In conclusion, knowledge of subsurface irrigation systems had been advanced in the former studies mostly by analyzing the measurements and evaluations of the traditional irrigation systems. Unlike the former period, the advancement in knowledge has been produced in the current period by introducing new subsurface irrigation systems and more concentration by the order of measurements, evaluation, and designing, respectively.

Keywords: Irrigation Systems, sub-Irrigation, subsurface irrigation, water movement in soil, wetting patterns

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INTRODUCTION

Subsurface irrigation defined by Camp (1998) is the method of applying irrigation water directly into the root zone of the soil profile. In contrast with surface irrigation systems, subsurface irrigation systems highly reduce human contact with irrigation water which sometimes is not freshwater (Qiu et al., 2017). According to Massatbayev et al. (2016) the main components structured the properties of subsurface irrigation are emission products, construction methods, materials, and packing of the soil. Furthermore, the vital advantage of subsurface irrigation systems is reducing the losses such as evaporation and surface runoff comparing to the surface irrigation (Montazar et al., 2017). Over the past two decades, subsurface irrigation systems had widely developed. Researchers discussed various aspects of subsurface irrigation systems such as design, operation, evaluation, measuring the wetting fronts, or producing new irrigation products. Also, methods of research studies used to achieve these purposes has been changed.

Various methods have been used to review subsurface irrigation systems by researchers. In this aspect some review papers can be mentioned. Ayars et al. (1999) summarized 15 years of research studies in a subsurface drip irrigation system to identify limitations and future studies, where they addressed the impact of soil type on selecting irrigation interval needed to be further research. Bastiaanssen et al. (2007) used a technique of SWOT to analyze the flow of water in unsaturated soils and described the solutions methods for managing irrigation systems. They concluded that common sense was not enough for developing irrigation systems as it needed the optimal solutions as well. Furman (2008) reviewed the subsurface flow of irrigation systems using mathematical forms whereas they concluded that both accuracy and applicability were required for subsurface irrigation systems to measure the water distribution in the soil profile. Ayars et al. (2015) discussed the status of subsurface drip irrigation systems in California by reviewing the current research studies and the on-farm practices and they found that subsurface drip irrigation had many advantages and could be considered as an effective tool to increase water usage efficiency. Rudnick et al. (2019) reported the results and highlighted future research areas of limited irrigation strategies conducted by research studies in irrigation systems where they noted that the optimal practice of irrigation depended mainly upon irrigation system type, soil moisture content, market value, and initial cost.

Research studies of subsurface irrigation systems need successive contributions (Singh, 2014c) and periodic overview because of the continuous development. Recently, researchers developed various subsurface irrigation systems by introducing either a new component or new systems. Engineering applications in automated and mechanized irrigation systems are still under research and development (Hudzari et al., 2013). Besides, irrigation systems are modified to overcome the topographical obstacles (Razali et al., 2016). Furthermore, a comparison between outcome benefits of using different subsurface irrigation systems is the main factor of continued and increased usability of these systems (Camp et al., 2000). Also, a substantial amount of irrigation water can be saved using innovation strategies compared to traditional irrigation systems (Azhar et al., 2014). Diversity in research studies is not only in irrigation systems but also in the objectives and methods of the research. Likewise, this diversity may change from each period to anther because of the technological and knowledge development. Therefore, a comparison and general overview of former and current research studies is required to discovery the diversity of research regions of subsurface irrigation systems.

The main purpose of this review is to preview the trend and diversity in research studies of subsurface irrigation systems by comparing the advancement in knowledge of subsurface irrigation systems in the past two decades. For instance, the trend represents the popularity of different topics in subsurface irrigation systems. Two periods of five years 1995-1999 and 2015-2019 were selected to reflect the research studies at the beginning and end of the comparison period. The former period indicates the later studies and the current period indicates the recent studies. Additionally, the objectives, methods, limitations, and the irrigation systems of the research studies in subsurface irrigation systems are analyzed.

MATERIALS AND METHODS

In this paper, a statistical sorting method was used to analyze and compare published research papers of subsurface irrigation systems. The general criteria used to select the papers and the description of the analysis method can be explained in detail in the following two sections.

General Criteria of Papers Selection

Two periods of time were selected of 20-years in range to represent the trend of research at each period. The first period was from 1995 to 1999 and the second period was from 2015 to 2019. A period of five-years had been used to represent the nature of the research published in the past and present as it was sufficient time to clarify the common research path. Moreover, to the absence of significant technological changes during the five-year period, which would not affect the nature of scientific research. The range of 20-years was used as a separation time range of the present period from the earliest past which was long enough to represent the differences because of the cognitive developments in the research trend.

Papers selected to be presented in this review were found using keywords which were directly related to the subject of the review. Since the subject of this review is the subsurface irrigation systems, keywords used to find the required papers were subsurface irrigation, wetting fronts, and irrigation systems. Furthermore, a research type of paper was selected to identify the required papers. These keywords had been searched in the Science Direct and Springer database.

Literature Classification Method

Research papers were classified by their objectives, methods of research, limitations, and the types of irrigation systems. This classification method presents the advancement in knowledge of the research studies by the categories of objectives and irrigation systems. Categories of methods and limitations represent the technological effectiveness of the research. These four categories give a good indication to compare the development of research trends in a 20-years range.

The first category is the research objectives which describe the distribution of selected papers according to their purpose which presents the general trend of knowledge. Four subcategories for classifying papers according to the objectives. The subcategories are design (DE), evaluation (EV), measurements (ME), and management (MA). These subcategories indicate the popularity of knowledge directions by presenting the distribution of research objectives per each period.

The second category is the research methods that present the common methods used by researchers to achieve their aims. This category indicates the technological development effectiveness specially to illustrate the differences between former and current research studies. Seven subcategories of research methods can be used to classify the research papers which are laboratory and on-field experiments (EX), numerical (NU), analytical (AN), optimization (OP), statistical (ST), economical (EC), and other (OT). Laboratory and on-field experiments usually adopt the case study or validate simulation models which is extremely helpful to understand what is the real behavior of the system in the real test (Fernández-Gálvez, et al., 2019). Simulation and optimization are commonly used in research methods for designing, managing, planning, and operating irrigation systems (Hantush & Marino, 1989; Huang & Loucks, 2000; Huang et al., 2012; Kite & Droogers, 2000; Loucks, et al. 1981; Mantoglou, 2003; Matanga & Mariño, 1979; Singh, 2013, 2014a, 2014b, 2014c; Tabari & Soltani, 2013). Also, mathematical and numerical approaches are widely used by researchers to represent specific purposes such as calculating the wetting fronts in soil profiles (Dawood & Hamad, 2016). Some researchers prefer to use more than one method for validating or comparing purposes therefore, research studies that used more than one method were classified and added into the existing methods. These subcategories of research methods can also indicate the reliability and the popularity of the adopted methods which can be interpreted from the rate of usage.

The third category is the research limitation. This category explains how technological development overcomes the difficulties faced the research. The research limitation reported in the literature is mainly on the dimensional presentation of the results and the soil types used in the research. The reason for using 2D or 3D representation is to show the ability of technological development in overcoming the research difficulties such as on-field measuring wetting fronts and simulation of water movement through time in the soil profile.

This category is usually considered as a challenge for researchers to overcome because the flow in the soil profile is unsaturated and needs visualization to be measured. Thus, presenting this category introduces the advancements in research methods and how it has impacted the quality and quantity of the result.

The fourth category is the type of irrigation system used in the research papers. Irrigation systems are developed through years of research projects. Therefore, it is important to sort the research papers according to the type of irrigation systems that indicate both the technological and knowledge developments. Irrigation systems which mentioned in this category are surface drip irrigation (SDI), subsurface drip irrigation (SSDI), subsurface membrane irrigation (SMI), subsurface irrigation pipe (SIP), optimized subsurface irrigation system (OPSIS), subsurface line source (SLS), surface irrigation (SI), irrigation basin (IB), micro-irrigation (MI), sprinkler irrigation systems (SIS) and baked clay pipes (BCP). Similarly, system products can be considered as a valuable addition to modify the typical system such as ceramic emitter (CE), suction emitter (SE), and rubber-based emitter (RB). Some research studies used more than one irrigation system for comparison purposes, so the classification considers all systems used per the research paper.

RESULTS AND DISCUSSION

In this paper, 81 papers had been statistically reviewed with 41 research papers classified into former (1995-1999) and 40 papers in the current (2015-2019) period. In the following subsections, summarized literature review of the both periods, results, and brief discussions are provided according to the classifications that have been explained earlier.

The literature review can be summarized in the two periods of five-years to show the sequence and type of resultant developments of each period. In the following paragraphs, the literature review is presented according to the sequence of the years which gives a good overview to compare between these two periods.

Review of Literature of 1995-1999

In 1995, most of the selected papers in subsurface irrigation systems were focused on management and measurements. For example, a research paper by Varshney (1995) discussed irrigation methods such as surface irrigation systems, sprinkler irrigation, drip irrigation, micro-sprinkler irrigation, and subsurface irrigation. He concluded that although subsurface irrigation could control the water content in the soil profile, it was still limited to be used just in arid areas because this method was uncommon for the farmers to be used in that time. Another paper conducted by Singh et al. (1995) presented the main idea of an automated irrigation schedule system that tested at the field to compare the results with a typical irrigation schedule. The system showed the ability to optimize irrigation water use.

In 1996, the majority of the research studies in subsurface irrigation systems were in measurements and evaluation. A study by Lacroix et al. (1996) introduced a measuring method to estimate the water balance which was verified by on-field experiments. They concluded that the method needed further calibration with field experiments to be more precise. Besides, Snyder et al. (1996) performed a survey of irrigation methods in California and compared them with previous surveys. The results showed that drip and sprinklers irrigation systems became popular more than before in contrast with the traditional methods.

In 1997, the objective presented in most of the selected papers was measurement techniques. For instance, a research paper by Esfandiari and Maheshwari (1997) developed an optimization method to estimate infiltration parameters of furrow irrigation method which gave a good accuracy by comparing with on-field results. Witelski (1997) analyzed the relation between wetting fronts with the boundary condition in soil profile using the perturbation method which indicated a high accuracy by comparing to solutions produced by numerical simulations.

In 1998, selected papers of subsurface irrigation were also focused on measurement. For example, Parlange et al. (1998) solved the nonlinear diffusion equation using an approximate analytical method for arbitrary boundary conditions which presented a well accurate performance. Also, Felsot et al. (1998) used on-field best management practices for reducing deep percolation of surface and subsurface drip irrigation. They concluded that it was difficult to measure the water distribution around the emitters.

In 1999, research studies of subsurface irrigation concentrated in measurement and design. For instance, a paper conducted by Meshkat et al. (1999) introduced a sand tube irrigation technique to reduce evaporation effectiveness on drip irrigation. Experiments and 3D simulations had been conducted in this study. The results showed that the technique could be used to reduce evaporation by more than 25 percent comparing to the typical surface drip irrigation. Furthermore, Barth (1999) developed a subsoil irrigation system that could be used to improve the performance of irrigation with minimum maintenance and a longer life span comparing to other irrigation systems.

The classification of research papers published in the former period is as presented in Table 1.

Table 1
Literatures classification of the former period (1995-1999)

Author (year)	Objectives	Methods	Limitations		Irrigation system
			Dimension	Soil type*	
Lacroix et al. (1996)	ME, MA	NU	OT	NM	MI, SI

Table 1 *(Continued)*

Author (year)	Objectives	Methods	Limitations		Irrigation system
			Dimension	Soil type*	
Varshney (1995)	MA	OT	OT	NM	SDI, SI, SIS, MI,
Singh et al. (1995)	MA, DE	OP, EX	OT	SC	SIS
Kandil et al. (1995)	MA	NU	OT	SC	SDI
Lockington and Parlange (1995)	ME	AN	1-D	NM	SI
Oad and Sampath (1995)	ME, EV, MA	EX, AN	OT	NM	SI
Ross et al. (1995)	ME, EV	AN, NU	2-D	S	NM
Scaloppi et al. (1995)	ME	NU, EX	OT	NM	SI
Snyder et al. (1996)	ME, EV	ST, OT	OT	NM	SI, MI, SDI, SSDI
Warrick and Shani (1996)	ME	EX, ST, AN	OT	SL	SSDI
Batchelor et al. (1996)	MA, EV	EX	OT	SCL	MI, SDI, BCP
Hansona et al. (1997)	ME, EV	EX, ST	OT	SL	SI, SDI, SSDI
Hilfer and Øren (1996)	ME	AN, EX	NM	S	NM
Izadi et al. (1996)	ME, EV	EX,	1-D, 2-D	SiL	SI
Kapoor (1996)	EV	AN	2-D, 3-D	S, L, C	NM
McClymont and Smith (1996)	EV, ME	OP, AN	OT	NM	SI
Panda et al. (1996)	MA	OP, AN	OT	SL, LS	SI
Rimmer et al. (1996)	EV, ME	EX	2-D	NM	NM
Ross et al. (1996)	ME,	NU, AN	1-D	S, C	NM
Shani et al. (1996)	EV, ME	EX, AN	OT	SL, SiL, CL	SSDI
Witelski (1997)	EV	AN, NU	OT	NM	NM
Willis et al. (1997)	ME	EX	OT	C	SI

Table 1 *(Continued)*

Author (year)	Objectives	Methods	Limitations		Irrigation system
			Dimension	Soil type*	
Esfandiari and Maheshwari (1997)	DE, EV, ME	EX, OP	OT	C	SI
Andreu et al. (1997)	ME, MA	EX	3-D	LS, SL	SDI
Amali et al. (1997)	ME, EV	EX, ST	OT	CL, SCL	SSDI, SI
Burt et al. (1997)	MA, EV, DE	OT	OT	NM	SI, SDI, SSDI, SIS, MI
Clemmens and Burt (1997)	EV, ME	ST	OT	NM	NM
Comparini and Mannucci (1997)	ME	AN	1-D	GPM	NM
Dale et al. (1997)	ME, DE	AN	1-D	GPM	NM
Furati (1997)	ME, EV	AN	1-D	GPM	NM
Kerkides et al. (1997)	EV, DE	AN,	1-D	GPM	SIS
Parseval et al. (1997)	ME	AN, EX	1-D	GPM	NM
Valiantzas (1997)	ME	NU, AN	OT	GPM	SI
Parlange et al. (1998)	ME	AN	1-D	GPM	SI
Felsot et al. (1998)	ME	EX	1-D	SL	SSDI
Ghanem and Dham (1998)	DE, EV	NU, ST	2-D	GPM	SI
Alazba (1999)	DE, ME	AN	OT	GPM	SI
Meshkat et al. (1999)	DE, ME	NU, EX	2-D	SiL, S	SDI
Barth (1999)	DE, MA	EX,	OT	NM	SLS
Connell (1999)	ME	AN, NU	1-D	S, L, C	NM
Coelho and Or (1999)	ME, EV	EX	2-D	SiL	SDI

*Symbols indicating the type of soil are: not mansion (NM), general pours media (GPM), sand (S), clay (C), silt (Si), loam (L), sandy clay (SC), sandy loam (SL), sandy clay loam (SCL), silty loam (SiL), loamy sand (LS), clay loam (CL), and sandy clay loam (SCL).

Review of Literature of 2015-2019

In 2015 and 2016, the selected research studies in subsurface irrigation systems focused mainly on the measurements. For example, Han et al. (2015) conducted on-field experiments and 2D simulation studies to measure the distribution of soil moisture content, which created by drip irrigation with mulch on the soil. Analysis of moisture content distribution that was created by 2D Hydrus showed a good agreement with the on-field experimental results. The 2D Hydrus model was found suitable to support the design and development process of a drip irrigation system in case of mulch on the soil surface. Another study conducted by Ali and Ghosh (2015) proposed a method for estimating the size-changing of wetting fronts in different soil types using numerical analysis and on-field verification where the results showed a high accuracy and could be applied into irrigation field to compute wetting fronts. Dawood and Hamad (2016) formed a set of equations by performing a set of numerical simulations using 2D Hydrus and on-field experiments to forecast the wetting fronts created by surface point source considering the variety of soil types which indicated highly accurate results.

In 2017, the selected papers in subsurface irrigation systems concentrated mainly on measurements, design, and evaluation. Honari et al. (2017) conducted a statistical approach to evaluate the ability of 3D Hydrus to simulate soil water content in field conditions which the results showed that the program could be used for simulating these kinds of cases. Also, Adams and Zeleke (2017) performed an on-field experimental study to illustrate the diurnal effects on irrigation efficiency and the study results pointed out that irrigation process for shallow root zone needed to be at the afternoon time to increase the irrigation efficiency.

In 2018, the majority of selected papers were also focused on measurements. As Al-Ghobari and Dewidar (2018) performed on-field experiments to test the strategy of deficit irrigation combined with surface and subsurface drip irrigation systems. The results of this study showed that combining deficit irrigation strategy with each of these irrigation systems could improve the irrigation productivity. Ren et al. (2018) derived a mathematical model for drip irrigation lateral and formulated an equation to represent the emitters discharge. They concluded that one of the main affected parameters on the hydraulic performance of laterals was the soil properties. Also, Fan et al. (2018b) simulated a vertical line source in HYDRUS to study the effect of influencing factors on the accumulating infiltration. The created empirical forms required further on field research studies to measure the wetting patterns and evaluate the created empirical models.

In 2019, the majority of papers of subsurface irrigation systems were concentrated in measurements. For example, an optimization study of designing subsurface irrigation systems conducted by Sakaguchi et al. (2019). They concluded that the recommended design parameters depended upon soil type, climate condition, irrigation intensity, and plant type. Another paper conducted by Cai et al. (2019a) was to test a ceramic patch in a subsurface irrigation line to control the saturated zone in soil profile created by the pressure head applied on emitters. They found there was a relationship between pressure head, ceramic properties, and soil properties. Also, Lima et al. (2019) indicated that using a new irrigation product named permeable membrane could be used as a solution to increase water use efficiency and maximize the irrigation management. Furthermore, paper published by Elnesr and Alazba (2019) to simulate wetting fronts created by subsurface drip irrigation using 3D and 2D HYDRUS. They concluded that 2D simulation could be used confidently by simulators.

The classification of research papers published in the former period is as presented in Table 2.

Table 2

Literatures classification of the current period. (2015-2019)

Author (year)	Objectives	Methods	Limitations		Irrigation system
			Dimension	Soil type*	
Sakaguchi et al. (2019)	DE	NU, OP	2-D	NM	SIP
Al-Ghobari and Dewidar (2018)	ME, EV	EX, EC	OT	CS	SDI, SSDI
Saefuddin et al. (2019)	ME, EV, DE	NU, EX	3-D	Si, S	SSDI
Cai et al. (2019a)	ME, DE	AN, EX	OT	Si, L	SSDI, CE
Elnesr and Alazba (2019)	ME, EV	NU	2-D, 3-D	S, LS, SL, L, Si, SiL, SCL	SSDI
Gu et al. (2017)	DE, MA	NU, EX, OP, OT	OT	NM	SSDI
Lima et al. (2019)	ME, DE	EX	OT	NM	SMI
Feng et al. (2017)	ME	EX, ST	OT	CL, C	SIP
Ren et al. (2018)	ME, DE	AN, EX	OT	S, L, SL	SSDI
Ren et al. (2017)	ME, DE	AN	OT	NM	SSDI
Cai et al. (2017)	ME, DE	EX, NU, ST	OT	CL	CE
Liu et al. (2019)	ME, EV	EX, ST	OT	L	SSDI
Grecco et al. (2019)	ME, EV	NU, EX, ST	2-D	SL	SSDI
Jiang et al. (2019)	ME	NU, EX, ST	2-D, 3-D	S, Si, C	RB

Table 2 *(Continued)*

Author (year)	Objectives	Methods	Limitations		Irrigation system
			Dimension	Soil type*	
Cai et al. (2018)	ME, DE	NU, EX, ST	2-D	L	CE
Fan and Li (2018)	ME	EX, ST	OT	C, SiL, S	SSDI
Ghazouani et al. (2019)	ME, EV	EX, NU, ST	2-D	NM	SSDI
Cai et al. (2019b)	ME, EV	EX, NU, ST	2-D	CL, SL, S, LS, Si, SiL, SCL, CL, SiCL, SC, SiC, C	CE
Gunarathna et al. (2018)	ME, EV	EX, ST, OT	OT	NM	OPSIS
Gunarathna et al. (2017)	EV, DE	NU, ST, OP	OT	NM	OPSIS
Ding et al. (2019)	EV	EX, OT	OT	SL, S	SDI
Li et al. (2019)	ME, EV	EX, ST, OT	2-D	LSi, Si, LS, SL, S	SDI
Zhang et al. (2017)	ME, EV	EX, NU, ST	2-D	L, SiL, SL	SDI, SI
Castanedo et al. (2019)	EV	NU, ST	2-D	SL, SiL, CL	SI
Fan et al. (2018a)	ME	EX, NU, ST	2-D	S, SiL	CE
Fan et al. (2018b)	ME	NU, ST	2-D	CL, SiL, L, SL, S	SLS
Han et al. (2015)	ME, EV	EX, NU, ST	2-D	SiL	SSDI
Adams and Zeleke (2017)	ME	EX, ST	OT	SCL	SDI
Dawood and Hamad (2016)	ME	AN, EX, NU, ST	2-D	SiCL, S, LS, SL, SCL, L, SiL, Si, C, SC, SiCL, SiC, SSiL, CL	SDI

Table 2 *(Continued)*

Author (year)	Objectives	Methods	Limitations		Irrigation system
			Dimension	Soil type*	
Martínez de Azagra Paredes and Del Río San José (2019)	DE, ME	AN	2-D	GPM	SE
Khalil and Abid (2019)	ME	AN, EX, NU, ST	2-D	SL	SDI
Abid and Abid (2019)	ME	AN, NU, ST	2-D	LS, SL, L	SSDI
Ali and Ghosh (2015)	ME	AN, ST	OT	LS, L, CL, SC	IB
Hatiye et al. (2018)	ME	AN, NU, EX, ST	1-D	SL	SI
Honari et al. (2017)	EV	EX, NU, ST	3-D	L	SIP
Kacimov et al. (2018)	ME	AN, NU	2-D	L	SIP
Naghedifar et al. (2019)	ME	NU	2-D	C, L, S	SI
Reyes-Esteves and Slack (2019)	ME	EX, NU	2-D	CL, SCL	SIP
Soulis and Elmaloglou (2016)	MA	EX, NU, ST	2-D	LS, Si, SiL	SDI
Zheng et al. (2017)	MA, ME	EX, NU, ST	1-D	LS, S, LS, SiC, S	SI

*Symbols indicating the type of soil are: not mansion (NM), general pours media (GPM), sand (S), clay (C), silt (Si), loam (L), sandy clay (SC), sandy loam (SL),clay sand (CS), silty clay (SiC), loamy silt (LSi), silty loam (SiL), loamy sand (LS), clay loam (CL), sandy clay loam (SCL), silty clay loam (SiCL), sandy silty loam (SSiL), and sandy clay loam (SCL).

Research Objectives Category

The classification of research papers made based on their objectives was divided into main four subcategories. These subcategories were used to represent alternatives that had been adopted by researchers to express their research aim. For instance, the subcategory of measurement includes terms such as determine, predict, calculate, and relate. Subcategories management and evaluation used keywords such as schedule and examination, respectively. While the category of design covers terms like develop and introduce. These four subcategories can be represented a general themes of research objectives. The distribution of research papers according to the objective's categories for former and current periods is as shown in Figure 1.

Figure 1 indicates the main directions of knowledge produced by research studies for former and current periods. All objectives mentioned in the papers accounted to be a part of the final percentage for each objective category. As shown in Table 1 and Table 2, some papers for both former and current periods were aimed for multiple objectives, as illustrated in Figure 2. For this reason, percentages cannot be integrated to obtain 100 percent in resultant.

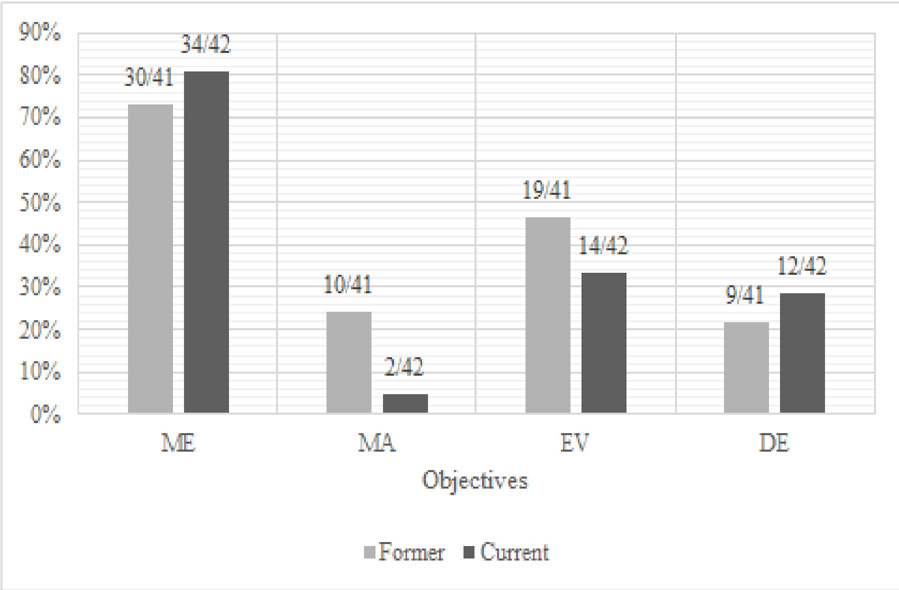


Figure 1. Research papers sorted according to the research objectives for former and current periods.

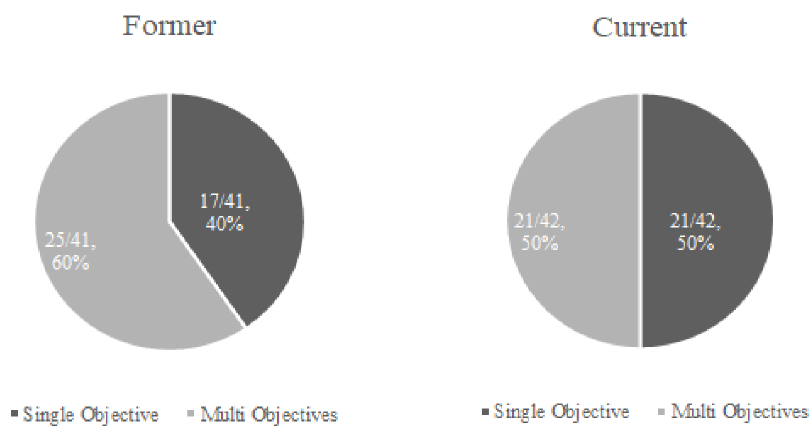
Papers published in the former period were distributed none uniformly throughout the four categories, which indicates that the general characterization of that period. More than 70 percent of the scientific research of the former period was interested in the measurement field. The evaluation field had gotten the second highest interests with 46 percent. Both categories of management and design had almost the same percentages of interests with 22 percent and 24 percent, respectively.

In the current period, the objectives of the research papers are also not uniformly distributed through the four categories but in a slightly different trend. Again, the measurement field had the highest percentage of 80 percent where it increased by almost

10 percent from the former period. Additionally, one-third of the research papers were concerned in the evaluation category which decreased more than 10 percent from the former period. The design category had been increased to 28 percent than in the former period, the most noticeable change was in the management category which highly decreased from 24 percent in the former period to 5 percent in the current period of the selected papers of subsurface irrigation systems.

As a result, the focusing of the papers in both periods were on measurements in the most of them and they had moderate concentration in evaluation and designing objectives.

Papers aimed for single or multiple objectives depending upon how these objectives are connected. Sometimes, the main objective needs for obtaining more data which produces anther supportive goal. The use of single or multiple objectives has also been changed during the past 20 years as shown in Figure 2 Whereas, 60 percent of the papers were published in the past were aimed for multiple objectives. This percent had been reduced in recent research studies to be 48 percent. This difference may indicate that the researchers were focused more on the branches of the single objective research.



(a) *(b)*

Figure 2. Percentage of research papers using single or multiple objectives in a) former and b) current periods.

Research Methods Category

Researchers used different methodologies available at their time to achieve the research objectives. In this subsection, a statistical overview of the methodologies of research papers is provided. The distribution of research papers according to research methods is presented in Figure 3. Since some papers used more than one method to achieve the research aim as presented in Figure 4, all methodologies used per paper had been accounted for. For this reason, percentages presented cannot be integrated into 100 percent.

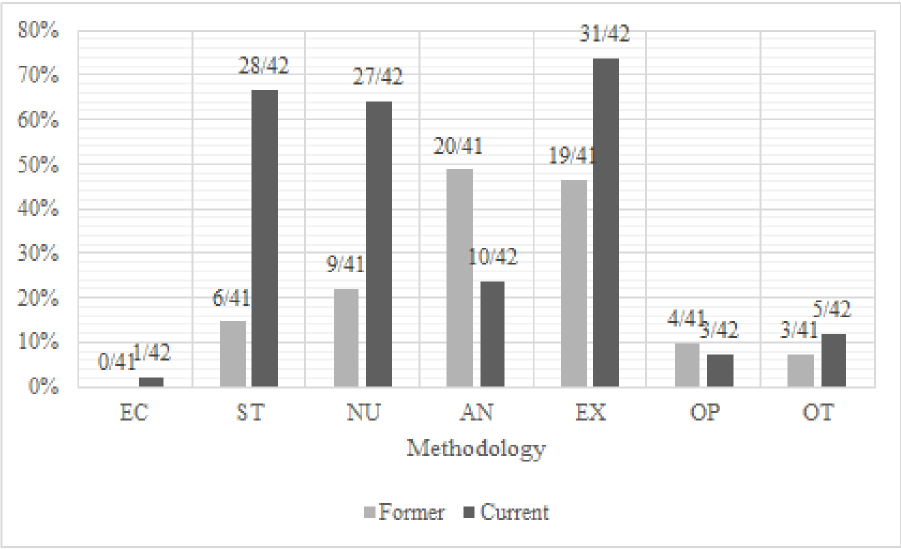
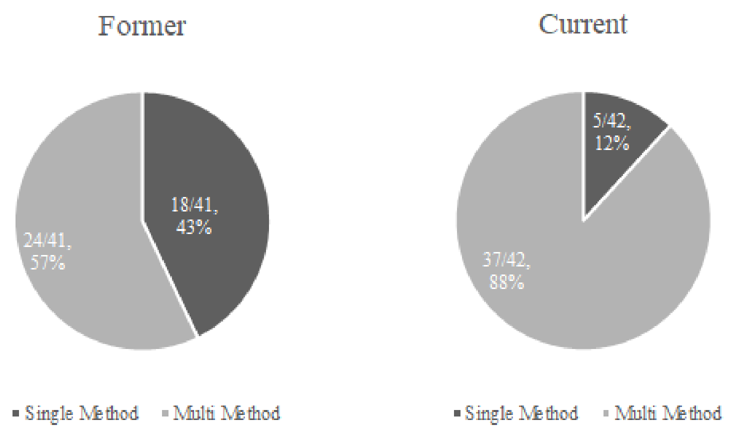


Figure 3. Research papers distributed according to research methods for former and current periods.



(a) (b)

Figure 4. Percentage of research papers that used single or multiple methods for a) former and b) current periods.

The two foremost methods in the former period were experimental and analytical methods in which 46 and 49 percent of research adopted these methodologies, respectively. On the other hand, the economic study was not used by any research of the selected papers. Percentage of research papers reported statistical, numerical and optimization methods in subsurface irrigation systems are 15, 22, and 10 percent, respectively, of the total selected papers. Research studies used survey, explanations, or discussing the subsurface irrigation systems were summarized in other methods which are covered in 7 percent of the selected papers. Two indications can be recognized from this distribution. The first indication is the analytical and experimental methods were popular in the former period which is a reason that may be due to the availability of these methods compared to the others. The second indication is the reliability of these methods that encourages the researchers to use them.

Research papers in the current period show a wide distribution of research methods. However, the experimental method was still preferred with an increase of usage by more than one-quarter to 73 percent. The analytical method decreased with the same ratio to 25 percent of the selected papers. In addition, both statistical and numerical methods increased used by 65 percent of the total research studies. On the other hand, optimization and economical methods adopted in 8 and 3 percent of the research, respectively. Other methods increased comparing to the former period to 10 percent of the current papers.

Technological development over the past 20 years has allowed researchers to use research methods such as numerical and statistical more than before. As these methods became available, more accurate, and easier to use, which made these methods more popular among researchers.

Figure 4 shows research papers that presented a single or multiple method to achieve the research aim. Single and multiple methods presented in 44 and 56 percent of the papers published in the former period respectively. That indicates a good availability of various types of methodologies in the former period. In the current period, researchers using more multiple methods in which the multiple methods were presented in 88 percent of the recently published papers. This change can be considered a huge step in scientific development which supported by technological developments. Using multiple methods gives a good chance for researchers to calibrate these methods to get more accurate results. According to Table 2, one of the notable things in the recent period is that the experimental, numerical, and statistical methods commonly used together, and this approach exists together in 29 percent of the recently published papers. This fact indicates the calibration development to create a larger tested area, accurate results, minimum cost of testing trials, and more models design.

Types of Irrigation Systems

In this subsection, irrigation systems used by researchers are sorted according to the subcategories as presented in Figure 5 is discussed. Although the main subject of this review is subsurface irrigation systems, some researchers use other irrigation systems to accomplish the research objectives, thus, irrigation systems that are not categorized under subsurface irrigation systems are also mentioned and accounted for in this statistical review. There are 15 categories of irrigation systems that have been accounted for that presented in the selected research papers for both former and current periods. Although, some research papers used more than one irrigation system, others did not mention the type of irrigation system or discussed the supplying system as a general point or line source. Nevertheless, irrigation systems was not mentioned or the general sources of the selected papers were accounted for under the not mentioned category.

In the former period, typical types of irrigation systems such as surface and subsurface drip irrigation, baked clay pipes, surface irrigation, micro-irrigation, sprinklers irrigation were presented in 32, 17, 2, 46, 10 and 10 percent of the selected research papers, respectively. While another 29% did not mention any category. Although the main subject of this review is the subsurface irrigation systems, it is worth mentioning that the surface irrigation was the most researched topics in the former period. While the subsurface drip irrigation, baked clay pipes, and subsurface line system represented the subsurface irrigation system. In summary, it can be said that past researchers had concentrated more on the existing irrigation systems and less focused on using new irrigation methods.

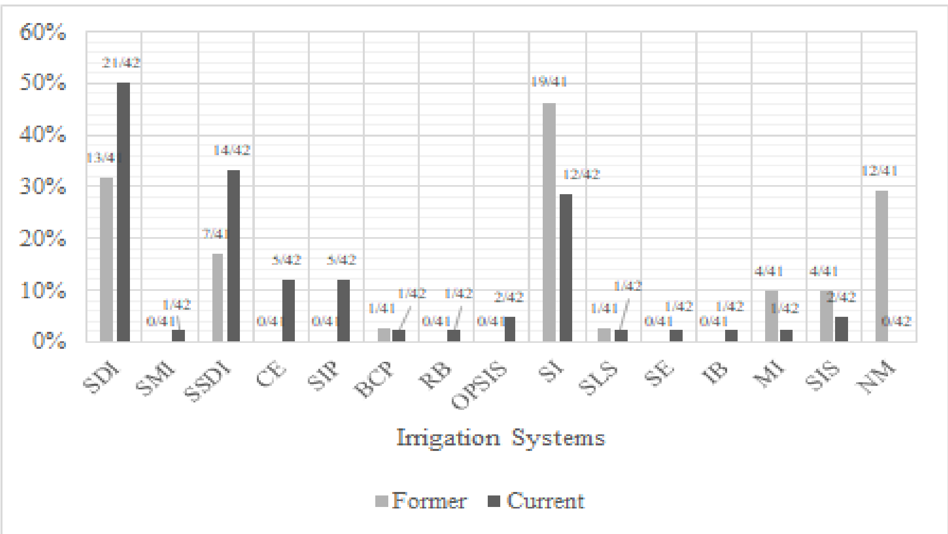


Figure 5. Research papers distributed according to irrigation systems used for former and current periods.

Recent papers present 14 types of irrigation systems which doubled the number of irrigation systems used by former papers. The current period witnessed a rise in developing new systems or new irrigation products. In addition, irrigation systems such as subsurface membrane irrigation, ceramic emitter, subsurface irrigation pipe, rubber-based emitter, optimized subsurface irrigation system, suction emitter, and irrigation basin are presented in 3, 13, 13, 3, 5, 3, and 3 percent of the current period respectively. Moreover, typical irrigation systems were presented differently in the papers of the current period in which surface drip irrigation system were presented in the half of the recent papers. Also, the subsurface drip irrigation research increased more than 15 percent and presented in the one-third of the research papers. It is also observed that the research on surface irrigation systems reported in the papers of the current period decreased by 29 percent of the papers. All the selected research papers in the current period had mentioned the irrigation systems and none of them used the general point or line sources. Some research papers used more than one irrigation system for both former and current periods as can be shown in Figure 6.

Not only that more than half of the research papers in the former period used a single irrigation system but also 17 percent of them used multiple irrigation systems as shown in Figure 6. On the other hand, a high concentration of using a single irrigation system was presented in research papers in which 93 percent of the papers used a single irrigation system, and only 7 percent used multiple irrigation systems. These statistics results give a good sign to indicate the direction of knowledge advancement. The trend shows the subsurface irrigation systems have developed to a new efficient irrigation systems or irrigation products.

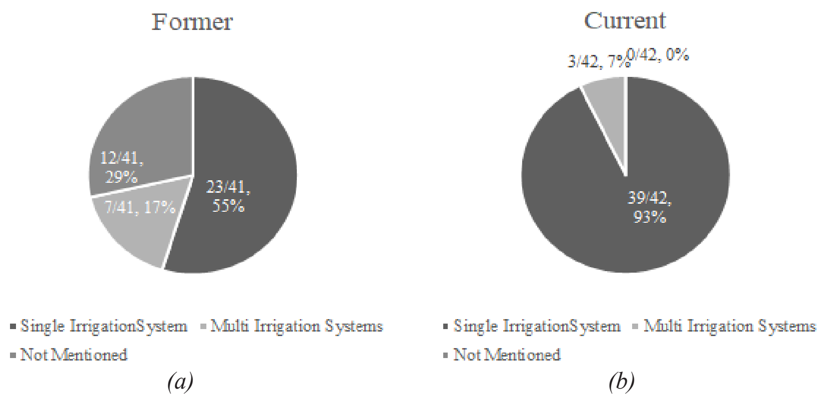


Figure 6. Percentage of research papers that used single or multiple irrigation systems for a) former and b) current periods.

Limitations

Two main limitations faced by researchers in the study of irrigation systems are discussed in this section. The first limitation is the soil type which represents one of the important components in the irrigation process. The second limitation is the dimension of the analysis.

Soil Type. Soil types had a lot of attention to the papers in both former and current periods to study subsurface irrigation systems. Research papers used different types of soils depending upon the availability and agricultural requirements. Figure 7 shows the distribution of research papers according to the soils type presented. However, some research papers used more than one type of soil, others used a general porous material as shown in Figure 8.

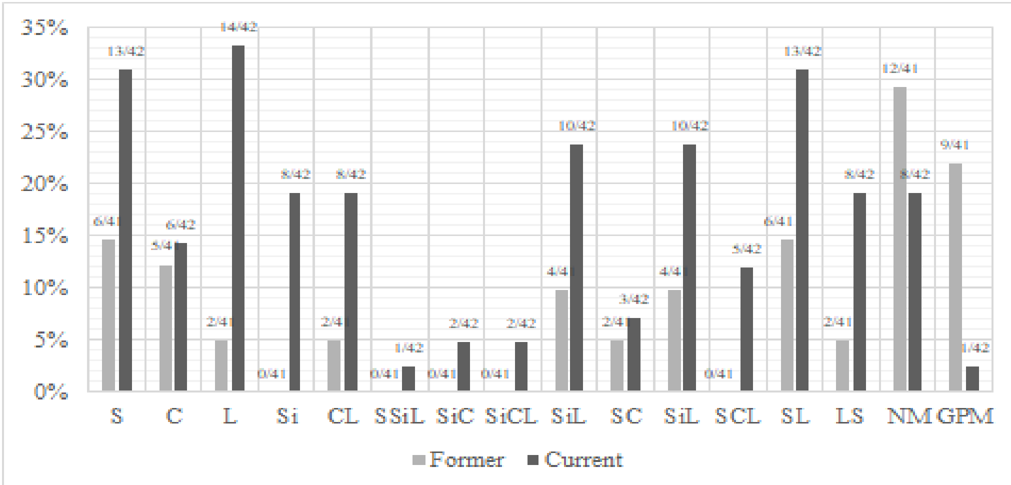
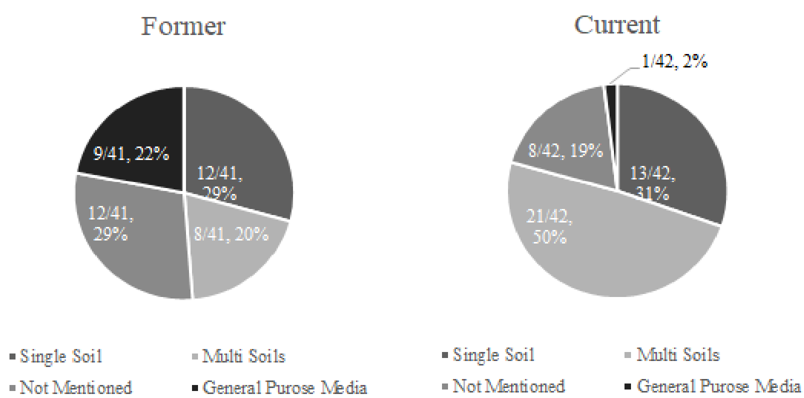


Figure 7. Research papers distributed according to soil type which used for former and current periods.



(a) *(b)*

Figure 8. Percentage of research papers that used single or multiple soils for a) former and b) current periods.

A wide range of soil types had been used in research papers of both former and current periods which 16 types of soils accounted for in this statistical view. Even though 10 types of soil were presented in the papers of the former period, 15 soil types had been presented in the current period. Due to the technological developments which allowed the researchers in the recent period to present more soils than the past period.

According to the former period, items of "general porous media" and "not mentioned" were the highest two among the other items with 29 and 22 percent, respectively. Soil types such as sand, clay, silty loam, and sandy loam were presented in between 10-15 percent of the research papers. Other soil types such as loam, clay loam, sandy clay, and loamy sand were presented in 5 percent of the total selected papers.

According to the current period, soil types such as sand, loam, and loamy sand were the highest presented in the research papers which 33 percent of the papers used these types of soils. In addition, items of clay, silt, clay loam, sandy clay loam, and sandy loam existed between 5 and 20 percent of the selected papers. Other soil types such as sandy silt loam, silty clay, silty clay loam, and sandy clay were presented in less than 10 percent of the research papers.

Recent papers were presented soil types more than the former research papers which indicate the effectiveness of technological developments. For example, computer programming such as Hydrus was widely used by recent papers to simulate the subsurface flow for different soil types which allowed the researchers to create simulating models more easily than before.

As shown in Figure 8, papers used single soil type, multiple soil types, general porous media, or not mention the soil type for both published papers of former and current. Single and multiple soil types were mentioned by the former papers in 29 and 20 percent respectively. However, papers of the current period had mentioned single soil type in almost the same percentage of 31, the multiple soil types had widely increased, used by 50 percent of the recent papers. In addition, general porous media reduced from 29 percent of the former papers into 19 percent of the recent papers. Also, the item of "not mentioned" has been reduced by 20 percent over the 20 years. In conclusion, recent papers used the advantages of technological development to test more types of soil per research. Programming software is one of the important technological developments which allow researchers to simulate types of soils more than before.

Dimensions. Dimensions are another important limitation issue in scientific research. Studying subsurface flow is considered as a challenge because it cannot easily be visualized and difficult to be measured. This is the main reason for simplifying the flow in the soil profile by specifying dimensions. Figure 9 shows the distribution of former and current papers according to dimensions of the subsurface flow presented in these papers.

Four items presented in Figure 9 of one (1-D), two (2-D), three dimensions (3-D) and other limitations (OT). However, one dimension presented in 27 percent of the former papers, only 5 percent of the recent papers presented the one-dimension flow analysis. In contrast, two-dimensional analysis had been used in 17 percent of the former papers and it is highly increased to be more than 50 percent of the recent papers. Likewise, using three-dimensional analysis had been increased over the 20 years from 5 to 10 percent of the selected papers. High portion of the papers mentioned other types of limitation such as experimental period, specific treatment, shape and size of introduced products, hydraulic properties of the ceramic emitters or sometimes not mentioned the limitation.

Research papers of subsurface irrigation systems in the current period have the following advantages comparing to the former period. Firstly, they introduce new irrigation components that will give the designers alternative options to provide users with an adequate subsurface irrigation system. Secondly, they are used more analysis methods per research which gives more reliability of the results than the former research studies. Thirdly, modern research papers have more focus on multiple objectives than the former papers. Fourthly, the latest papers tested much more soil types than the previous ones which improves the accuracy of measurements and prediction of subsurface flow.

On the other hand, recent research papers have disadvantages comparing to the previous papers. Firstly, in the most of papers in the current period used a single irrigation system per paper which reduced the chances of comparison with other irrigation systems. Secondly, the analytical method was less in use by the recent papers comparing to the latest papers which might reduce the opportunity of producing generalization forms. Thirdly, research in management and evaluation of the performance of subsurface irrigation systems had less focus on the current papers comparing to the former papers.

Technological development assists researchers in modifying the research methods to explore new research areas and investigate more materials with different methods. As a result, knowledge advancement is directly connected to technological development. Also, technological development increases the type of detail research but reduces the type of general research. Therefore, the trend of the subsurface irrigation systems in the current period is to measure the performance of novel irrigation systems components using experimental, numerical, and statistical analysis. On the other hand, the trend in subsurface irrigation systems for the former period is to measure and evaluate the performance of traditional irrigation systems using analytical and experimental methods.

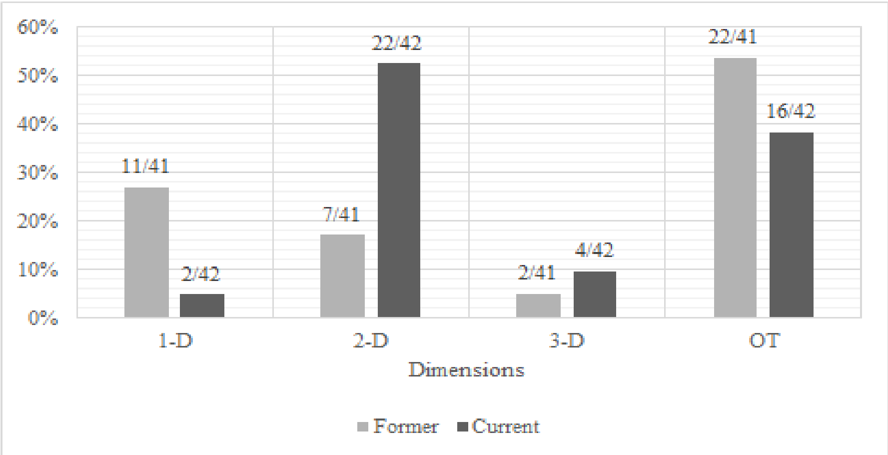


Figure 9. Research papers distributed according to dimensions which analyzed for former and current periods.

SUMMARY AND CONCLUSIONS

There are many differences between the papers of subsurface irrigation systems in former and current periods. In this review, the research papers had been classified by four categories to identify the trend of research topics and compare the differences in the advancement of knowledge resulted from the research studies and the effectiveness of the technological development on the research methodologies. Papers of former and current periods were classified by its objectives, method of study, irrigation systems, and research limitation.

In conclusion, papers of the both periods were focusing on measurements in the most of them and they have moderate concentration in evaluation and designing objectives. Multiple objective papers were presented in the former period more than the current period which gave more opportunity for using more research method and materials.

Even though, the selected papers were in the subject of subsurface irrigation systems, most of the papers in former period were presenting surface irrigation systems. In contrast with the recent papers which presented not only the higher in subsurface irrigation systems types but also lesser in using surface irrigation systems. Furthermore, more than 90 percent of the research papers in the current period used single irrigation system more than the past by almost 40 percent. The reason of this distribution is that the papers in the current period presented new irrigation systems such as subsurface membrane irrigation, ceramic emitter, subsurface irrigation pipe, rubber-based emitter, optimized subsurface irrigation system, and suction emitter.

Knowledge of subsurface irrigation systems had been advanced in the former studies mostly by analyzing the measurements and evaluations the traditional irrigation systems. On the other hand, knowledge had been advanced in the current period by introducing new subsurface irrigation systems and more concentration by the order of measurements, evaluation, and designing respectively.

In addition, almost 90 percent of the research papers in subsurface irrigation systems used multiple research methods higher than the past which presented 56 percent of the published papers. Experimental, numerical, and statistical methods were the major methods recently used by researchers. One of the noticeable changes was that the main research method widely used in the former period was the analytical method which was reduced by 25 percent of recent research studies.

The variation of soil types and dimensions of the analysis adopted in the research shows the effectiveness of the technological developments. Fifty percent of the recent research papers used multiple soil types more than the former research papers which presented in only 20 percent of the published papers. With respect to the dimensions of analysis adopted it has been observed that the one-dimensional analysis was commonly used in the former studies, but two-dimensional was the most used in the current period. These can be considered as good indications of the effectiveness of the technological developments which advances some research methods to become easier to be used by the researchers.

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