Kedir et al. Environmental Systems Research (2022) 11:17
https://doi.org/10.1186/s40068-022-00263-7

Environmental Systems Research

RESEARCH

Open Access

Analysis of water–energy–crop nexus indicators in irrigated sugarcane of Awash Basin, Ethiopia

Yusuf Kedir[1*], Belete Berhanu[2] and Tena Alamirew[3]

Abstract

Pressures on limited resources of water and energy in agriculture forced researchers to look for alternative approaches towards the solutions integrating the resources. Since the development of the water–energy–food (WEF) nexus concept, several methods including indicator approaches have been developed and are in use to analyze their linkages. The aims of the study have been to determine and compare the performances of sugarcane producing irrigation schemes and technologies in Awash Basin of Ethiopia. Water applied, input energy used and productivity of eleven irrigation schemes found in Wonji, Metehara and Kessem sugar factories have been used and the performances of each scheme were evaluated. Based on statistical analyses, irrigation schemes were grouped into gravity surface, pump surface and pump sprinklers. After normalizing the original data through min–max, performance scores were determined based on equal weight and entropy methods. Categorical assessments revealed that gravity surface schemes had the highest total input energy use and energy productivity scores while pump sprinkler schemes were better on the water applied, relative irrigation supply and water productivity indicators. However, regarding composite performance indicators or WEF nexus indices, pump surface schemes scored the highest followed by gravity surface schemes while sprinklers were the least. The study proved the emphasis of the sugar factories of the basin for crop productivity with the expenses of energy and water utilizations. Hence, improvements in water management of gravity surface schemes and energy utilization of sprinkler schemes were recommended as key solutions for balanced resource use as well as the overall sustainability of the sector.

Keywords: Composite indicator, Entropy weight, Min–max, Performance indices, Spider web

Introduction

The world is confronted with significant challenges in the way it manages and consumes its resources. Traditionally, energy, water and food (WEF) have been treated and intervention designed as if the relationship between the three was only casual. Little consideration has been given, for instance, to the impact on energy security and water resources of growing crops for industrial purposes. According to Siala et al (2017), as population, urbanization, and economic growth are exerting pressures on resources, effective and efficient use to minimize tradeoffs and maximize synergies are vital.

The connections between water, energy and energy (WEF) sectors, known as the WEF nexus, are becoming a major academic, policy, and societal topic which increasingly being discussed at global level. The challenges to managing water, energy, and food resources simultaneously and meeting multiple potentially conflicting objectives without compromising the resource base of any sector are urgent and need to be resolved as best as possible (Purwanto et al. 2021) which demands an integrated approach in which the systems are considered as a whole.

Different methods or approaches are developed to assess the WEF like water, energy, crop land or carbon

*Correspondence: yuskedd@yahoo.com; yuskedd@gmail.com

[1] Addis Ababa Institute of Technology (AAiT), Addis Ababa, Ethiopia
Full list of author information is available at the end of the article

footprints (Ghosh and Chakma 2019; Daccache et al. 2014; Silalertruksa and Gheewala 2018); linear programming (Chapagain et al. 2006; Yuan et al. 2018), and modeling and optimization (Nie et al. 2019) or a combination of them. Recently, the usefulness and use of WEF nexus indices and composite indicators to analyze complex and multidimensional issues has been recognized and gained tractions (Gómez-Limón and Riesgo 2008). Several studies such as Daher and Mohtar (2015), El-Gafy (2017), Ghosh and Chakma (2019), Liu et al. (2019), Mabhaudhi et al. (2019), Nhamo et al. (2020a), Sadeghi et al. (2020), and Wasihun et al. (2019) have emerged.

Composite indicators that integrate various interlinked measures into an index can be useful tools for measuring sustainability (El-Gafy 2017; Zhen and Routray 2003) and to evaluate and analyze strategies that link WEF with one number (Bizikova et al. 2013; El-Gafy 2017). Among other things (Zhen and Routray 2003), performance analysis with indicators will help to ensure early detection of problems encountered during implementation; identify successful strategies; ensure supply of quality information on performances; establish accountability for resource allocations, and create awareness among stakeholders.

While integrating WEF nexus indicators, El-Gafy (2017) provides a method for decision makers to analyze WEF nexus of crop production system at a national level. Ghosh and Chakma (2019) analyzed agricultural sustainability at micro level by developing a composite indicator of land, water and energy used for crop production. Liu et al. (2019) evaluated agricultural sustainability of Chenmengquan irrigation district of China based on WEF nexus. Nhamo et al. (2020a) defined WEF nexus sustainability indicators and developed a methodology to calculate composite indices to facilitate WEF nexus performance, monitoring and evaluation. Sadeghi et al (2020) applied a linear WEF nexus optimization for 14 crops planted in orchard, irrigated farms, and rain-fed farms of Shazand watershed of Iran targeting WEF nexus index (WEFNI) maximization.

However, there are still gaps in applying nexus assessment and methodologies because results of a study may not be used for another location due to several factors such differences in assessment purposes and scopes (Liu et al. 2017), lack of common definition, and framework (Purwanto et al. 2021). Most of the studies mentioned above were applied for crop production systems at national or watershed levels. A single effort so far on the use of composite performance indicators in the local context was the work of Wasihun et al. (2019). The study assessed WEF nexus in Wonji-Shoa, Metehara, and Finchaa sugar factories of Ethiopia by applying consumption, mass, and economic productivity indicators and WEF nexus index (WEFNI) at factory level. Despite its usefulness for the understanding of WEF relationships, the study did not consider various irrigation schemes and technologies existed in each factory and also energy inputs of irrigation water were not included.

Ethiopia is not only energy scarce country (PDC 2021) but also the irrigation sector is grappling with challenges such as poor water management (Kedir 2021). Irrigation schemes of Ethiopia consumed around 9 billion m^3 of water from which 3.2 billion m^3 belongs to Awash basin which has weighted mean irrigation efficiency of 33.67% (Kedir et al. 2021). According to unpublished report of Ethiopian Electric Power (2015), in 2015, the country generated a total of 17,396 GWh electric power from different sources of which agriculture consumed only 3.58%. The projections for 2025 are 83,720 GWh and 8.6%, respectively. Despite these concerns, the government is determined to pursue expansions of water saving but energy consuming technologies with the intention of improving the inefficient and low productive irrigation sector. The increasing use of sprinkler systems reaching more than 22,550 ha is a good example. The first dragline sprinkler of the country was installed in 1994 on 6204 ha of Finchaa sugar factory in the Blue Nile (Abay) river basin (Birhanu 2011). In 2006 and 2010, dragline and center pivot sprinklers on 3819 ha were installed in Wonji sugar factory (Kedir 2021). The recent Development Plan of Ethiopia has considered increasing the area extent of modern irrigation from 2 to 20% (Planning and Development Commission 2021) in the coming 10 years.

Most of sugarcane irrigated areas of Ethiopia are found in Awash basin. The crop is widely cultivated at large scales in which numerous energy consuming semi-mechanized farm operations, inputs and technologies such as gravity and pump dependent furrow and sprinkler methods are practiced. Sugarcane is water and energy demanding crop and at the same time both water and sugarcane are energy suppliers and users (Chamsing et al. 2006; Singh and Mittal 1992). However, water and energy use natures of the technologies are not the same and unless properly managed they have the potential to create resource imbalances. In the long run, a rise in energy and water prices or shortages of the resources will have serious consequences on profitability and sustainability of the production systems.

The motivations for the study are framed on the notions that sugar factories should be energy (for water pumping, fertilizer, machinery and so on) self-sufficient so that efficient resource utilizations at scheme level should be key sustainability agendas. One resource should not be compromised for the other. Besides, due to lack of technology-based quantified local data on the linkages between these limited resources, irrigation sector of Awash basin became vulnerable to WEF crises (Gebremeskel and

Mekonen 2015). Because sugarcane irrigation is a good example for WEF nexus due to strong competition over water for energy and water for food production (Liu et al. 2019), the questions investigated here are; how well WEF resources are efficiently utilized and linked in existing irrigated sugarcane production of the basin? What are the implications of introducing sprinkler technologies on water and energy consumptions and productivities?

In order to address the questions, assessments of the resources and quantifications of the linkages using nexus indicators are vital for local managements or decision makers (answering the first question) and policy makers (the second question). The paper assessed the situations based on data collected from 11 irrigation schemes with the help of six WEF nexus performance indicators. Based on relative weights of the indicators and composite indices, the schemes were categorically evaluated and compared. Details of the methodologies are presented in the following sections.

Materials and methods

Descriptions of Awash basin and the studied sugarcane schemes

Awash, one of the 12 river basins of Ethiopia, accounts 25% of national agricultural production; hosts more than 65% of total industries; is the second most populous basin next to Abay by inhabiting 18.6 million people; is fourth in areal coverage with 114,123 km^2; the seventh in annual runoff volume; and is the most intensively irrigated basin (AwBA 2018; Kedir et al. 2021). The basin lies between 7° 52′ 12″ to 12° 08′ 24″ N and 37° 56′ 24″ to 43° 17′ 2″ E.

Modern irrigation was started in this basin (Awulachew et al. 2007; Bekele et al. 2012; Haile and Kassa 2015) during the 1960s (Kedir 2021) and currently, 0.2 million ha (9% of the basin's rainfed croplands) is irrigated which is 32% of the national irrigated area (AwBA 2018; Yibeltal 2013; Kedir 2021). More than 2500 equipped irrigation schemes (Yibeltal 2013) of surface, dragline and center pivot sprinklers, and drip types are functioning. Almost 97.9% area is irrigated with surface methods from which around 87%, 10.6% and 2.4% are ditch-furrow, flexible pipe and basin method, respectively. Shares of sprinkler and drip systems are 1.46% and 0.64% (Kedir et al. 2021).

More than 50 crops are irrigated in Awash basin but maize, onion, sugarcane, cotton and tomato are dominant covering 73% irrigated area of the basin. In Ethiopia, sugar production is totally dependent on large scale irrigated sugarcane farms and currently around 100,000 ha is managed by eight sugar factories. Among them, Wonji, Metehara and Kessem factories cultivation a total area of 30,000 ha are found in Awash basin (Fig. 1) from which 11 irrigation schemes listed in Table 1 were used for this study.

Wonji sugar factory comprises Wonji main, Wake Tiyo, North Dodota and Wellenchiti Bofa schemes. Water source of these schemes is Awash River. Except Wonji pump scheme, the others use diversion weirs. Dodota center pivot and dragline schemes have common diversion weir called Dodota North while Wake-Tiyo pump dragline sprinkler use a separate weir.

Sugarcane farms of Wonji sugar factory broadly classified as Wonji main, Wellenchiti Bofa, Plantation schemes of Metehara factory use two diversion weirs constructed on Awash River. Merti weir delivers water for Merti gravity surface scheme while Abadir weir is irrigating Abadir gravity scheme. Kenifa and Abadir pumps are situated along main canals of Merti and Abadir gravity schemes.

Kessem sugar factory crushes sugarcane collected from schemes owned by the factory (2785 ha) and a private scheme (6000 ha). For the study, however, data collected from factory's scheme (KGS) was considered which diverts water released from Kessem dam.

Several electric and diesel driven irrigation pumps are operating at Wonji and Metehara plantations and main features of the major electric pumps are presented in Table 2.

Table 3 presents data related to cropped, harvested and irrigated areas of the studied schemes. Cropped area refers to the area covered by sugarcane crop. Harvested areas represent portion of cropped area harvested for sugar production.

The three sugar factories are expected to produce ethanol with an aggregate potential of generating 50 MW electric powers from bioethanol. Currently Metehara and Kessem generate 9 MW and 8 MW of electricity to cover their factory demands while Wonji sugar factory gets its electric power from the national grid.

Farm operations of irrigated sugarcane: an overview

All medium and large scale sugarcane plantations of the country are semi-mechanized irrigated farms and hence, every cultivation practices should synchronize with annual operational plan of the factories; in our case Wonji, Metehara and Kessem. The following descriptions were summarized based on field experiences substantiated with information collected from operation manuals of the factories.

Except minor differences, the major and common farm practices irrigated sugarcane can be grouped as seed cane growing, land development and preparation, planting and cultivation, and harvesting. The crop is propagated by vegetative means from cuttings of young canes previously planted. After preparing and planting of the seed materials, most of the operations are similar with

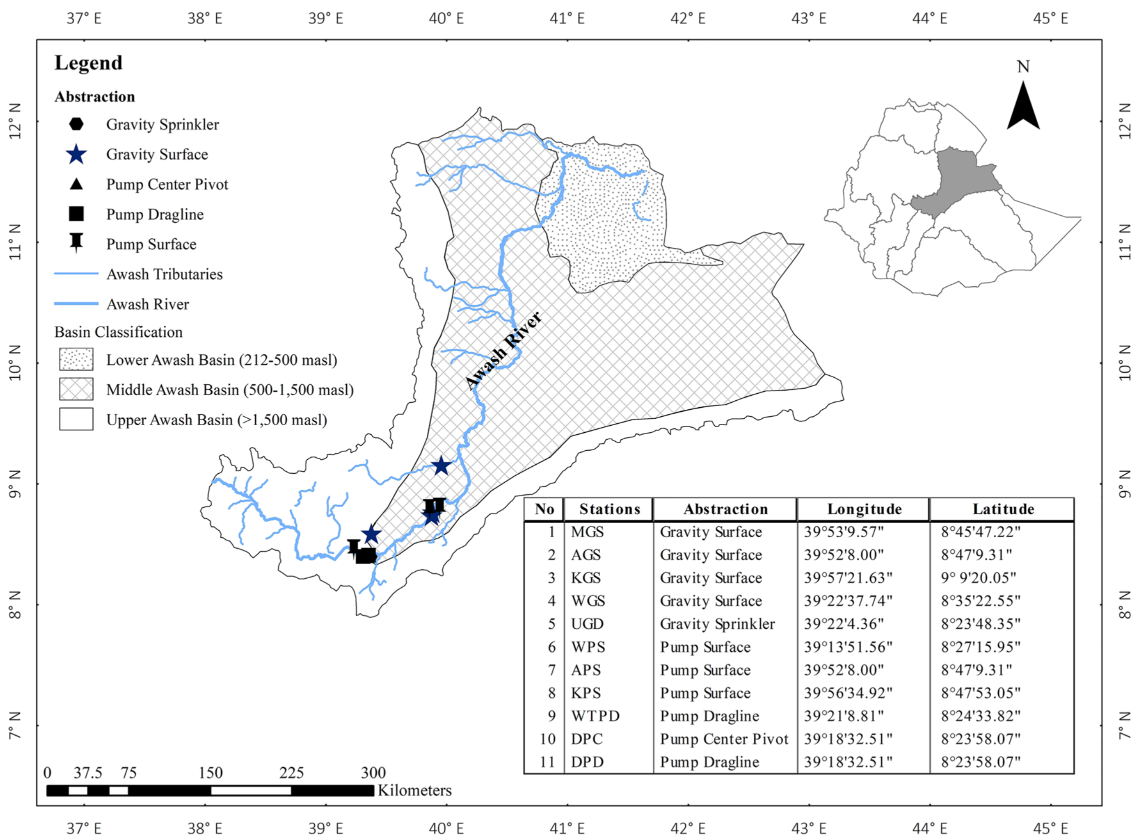

Fig. 1 Map displaying locations of studied irrigation scheme of the sugar factories found in Awash basin. Irrigation schemes of Wonji and Metehara are too close for the scale so geographical coordinates are included in the figure

Table 1 Main characteristics of the selected sugarcane producing irrigation schemes

No.	Schemes	Abbreviations	Sugar factories	Water abstractions	Field applications	Categories
1	Merti gravity surface	MGS	Metehara	Diversion	Furrow	Gravity surface
2	Abadir gravity surface	AGS	Metehara	Diversion	Furrow	
3	Kessem gravity surface	KGS	Kessem	Diversion	Furrow	
4	Ulaga gravity dragline	UGD	Wonji	Diversion	Dragline	
5	Wellenchiti gravity surface	WGS	Wonji	Diversion	Furrow	
6	Wonji pump surface	WPS	Wonji	Pumps	Furrow	Pump surface
7	Abadir pump surface	APS	Metehara	Pumps	Furrow	
8	Kenifa pump surface	KPS	Metehara	Pumps	Furrow	
9	Wake Tiyo pump dragline	WTPD	Wonji	Pumps	Dragline	Pump sprinklers
10	Dodota pump center pivot	DPC	Wonji	Pumps	Center pivot	
11	Dodota pump dragline	DPD	Wonji	Pumps	Dragline	

growing of the main sugarcane crops. Nursery management is totally a manual operation.

Matured seed canes will be planted on either old or new developed farm fields. Land development can be done in different modalities but all have more or less the same operations. For virgin lands, it is a one-time operation which covers clearing of trees and termite mounds, and land leveling. For other fields, after completing the cropping cycle removal of cane stable is needed so land preparation comprises uprooting, sub-soiling, ploughing,

Table 2 Main features of electric pumps of irrigation schemes excluding stand-by and booster pumps

No.	Schemes	Number of pumps	Pressure heads (m)	Discharges of each pump (lit/s)	Water sources
1	WPS	8	7	450	Awash river
2	APS	2	20	500	Main canal of AGS
3	KPS	6	30	280	Main canal of MGS
4	WTPD	3	45	210	Awash river
5	DPC	3	53	290	Awash river
6	DPD	6	74	290	Awash river

Source Own compilation from respective sugar factories

harrowing, and furrowing. Different tractors and implement models and sizes are used depending on soil type, topography, climate, irrigation system and etc. Number of tillage operations may differ and all the entire land preparation activities are diesel fuel based mechanical operations.

Planting, gap filling, moulding, weeding, chemical and fertilizer applications, ratoon reshaping, furrow corrections, irrigation, and cane pushing are common agronomic practices grouped under cultivation. Planting, gap filling, weeding, furrow correction and cane pushing are manual operations and moulding is done mechanically while chemical and fertilizer applications are semi-mechanized operations.

Diversion weirs and electric pumps are used to abstract the irrigation water from rivers or dams. The most common irrigation method is furrow system. Feld irrigation are either manually (for surface methods) or semi-mechanically (sprinklers) operated. In dragline system, the sprinklers are moved from one field to the next between irrigation sets. Operators change the locations of sprinklers at predetermined order and irrigation intervals while center pivots sprinklers have electric driven self-rotating mechanisms. Night time irrigation is common for sprinklers. Furrow irrigation is carried out by a group of human labors mostly 3–5 field operators irrigating 25–75 ha during 8 h of the day time. In both cases, numbers of labor depend on irrigation intervals. Mean irrigation interval for schemes at Wonji is within the range of 15–38 days. For Metehara and Kessem schemes, the irrigation intervals are around 25 and 15 days, respectively.

Chemical fertilizers and agrochemicals are used in varying amounts depending on recommended practices. Nitrogen (46% urea) and ferrous sulphate ($FeSO_4$) at Metehara, and urea at Wonji-Shoa and Kessem fields are applied. Manures or filter cake might also be used on selected fields. Weeds are controlled through hand weeding as well as mechanical spraying of chemicals. Harvesting is the last farm operation considered for the study in which cane burning and cutting are operated manually.

Data collection, determination of indicators and analysis approaches

The study was carried out in three steps which are briefly explained as follow.

Step 1: Water and energy consumption and productivity indicators

Matrices of water and energy consumptions and performance indicator to express WEF nexus at scheme level

Table 3 Historical mean annual cropped, harvested and irrigated areas, and total production and water applied (million m^3) of the studied irrigation schemes

No.	Schemes	Cropped areas (ha)	Harvested areas (ha)	Irrigated areas (ha)	Total production (tons)	Water applied (Mm^3)
1	MGS	6102.8	3539.6	4717.5	481,469.8	147.4
2	AGS	2485.4	1491.2	1921.2	201,028.6	60.2
3	KGS	2785.0	1671.0	2367.3	150,162.7	75.0
4	UGD	168.0	95.8	137.8	10,784.4	3.6
5	WGS	975.6	556.1	800.0	93,212.9	30.8
6	WPS	5630.0	3209.1	3378.0	340,559.8	63.2
7	APS	493.0	295.8	381.1	35,257.1	6.7
8	KPS	1265.0	759.0	974.1	93,058.3	16.4
9	WTPD	624.5	356.0	512.1	39,556.3	7.2
10	DPC	575.0	327.8	471.5	35,788.3	5.7
11	DPD	1684.5	960.2	1381.3	104,844.1	19.1
	Total	22,788.8	13,261.5	17,041.7	1,585,722.1	435.3

Sources Respective sugar factories

were suggested by scholars such as Fabiani et al. (2016) and Ahmad and Khan (2009) and the success of a given indicator depends on the availability of data and the motivation for its development (McGrane et al. 2018). Among the consumption and production indicators, the following indicators were used for assessment as the first step of the study. The indicators were used evaluated each of the irrigation schemes.

Irrigation water use This indicator is the total volume of irrigation water diverted or pumped in to a unit of sugarcane land expressed in m^3/ha. At the entrance main canals, at least one graduated staff gauge is installed. Graduated staff gauges are used to measure volume of water supplied to sugarcane fields. Starting from the beginning up to end of irrigation seasons, discharges of the canals were recorded and the total volumes of water applied were determined by multiplying mean discharges with the total time of flow. Then water used indicators were determined by dividing the total volume of water diverted by total area being irrigated during that specific period.

Input energy use This indicator represents the total input energy being consumed to produce sugarcane on a unit of land expressed in MJ/ha or GJ/ha. The amounts of inputs being used per hectare at each scheme were collected from sugar factories and converted into standardized energy unit i.e. MJ/ha.

The following equivalent energies of the inputs were used: equivalent energy of electricity is 11.93 MJ/kWh (Jackson 2009; Gundogmus 2006; Singh and Mittal 1992; Yavuz et al. 2014); diesel, 56.31 MJ/L (Sadeghi et al. 2020; Singh and Mittal 1992); human labor, 1.96 MJ/h (Karimi et al. 2008; Gundogmus 2006); irrigation water, 0.84 MJ/m^3 (Sadeghi et al. 2020; Zahedi et al. 2015); pesticides and herbicides, 92 and 238 MJ/kg (Sadeghi et al. 2020; Wakil et al. 2018; Kitani, 1999); tractor and farm implements, 64.8 and 62.7 MJ/h (Jackson 2009; Karimi et al. 2008; Kitani 1999; Sadeghi et al. 2020); nitrogen, 78.1 MJ/kg (Chamsing et al. 2006; Kitani 1999); ferrous sulphate, 17.4 MJ/kg (Chamsing et al. 2006; Kitani 1999); manure, 0.3 MJ/kg (Jackson 2009); sugarcane, 5.3 MJ/kg (Singh and Mittal 1992); cane straw, 16.1 MJ/ha (Vergara et al. 2021; Singh and Mittal 1992).

Land productivity The indicator represents yield obtained from a unit of sugarcane farm (ton/ha) and was determined by dividing the total amount of cane yield collected to mean harvested areas.

The above indicators were assessed and evaluated at scheme levels by analyzing the means, standard deviations, minimum, and maximum values. In this descriptive evaluation, except total input energy indicator, 5 years historical data were used. Due to data limitations particularly historical data for farm operation related activities, however, data collected for the year 2019/2020 were used to calculate total input energies of the schemes.

Step 2: Scheme categorization

The numbers of irrigation schemes being considered and evaluation parameters were large enough to complicate the comparative performance assessments and identification of the real factors playing decisive roles. Besides, the goal of the study was aimed at quantifying resource utilization performances of irrigation technologies and suggesting of comprehensive solutions which can be implemented across the sector. Reducing the numbers of variables through grouping of the irrigation schemes will simplify and help to solve such challenges. Based on pressure heads, the irrigation schemes were grouped into different categories and existences of significant differences among the categories were tested. Student *t* tests of single parameter ANOVA together with LSD mean separation techniques have been made at 5% of significant level.

Step 3: Categorical nexus performance comparisons

After grouping of the scheme, on top of water and energy use indicators mentioned above, the following four indicators were used for the assessments. While determining values of the indicators, values of irrigation schemes found in the same category were averaged.

Water–water (WW) This nexus performance indicator represents the relative irrigation supply (RIS) of an irrigation system or the relationship of irrigation water requirement of the crop and supply level computed as the ratio of total annual volume of irrigation water diverted or pumped to the total annual volume of net irrigation water demands of crops (Eq. 1).

$$\mathrm{RIS} = \frac{\text{Total volume of water applied } (\mathrm{m^3/ha})}{\text{Total volume of crop demand } (\mathrm{m^3/ha})} \quad (1)$$

CropWat 8.0 was used to determine net irrigation demands of sugarcane cultivated in each location based on planting dates, growth stages and crop coefficients and climatic data of the areas. Relevant data were collected from the research centers of the sugar factories.

Water–energy (WE) Nexus is a performance indicator used to measure the amount of energy consumed to supply a unit of water. It is also called Specific Energy and represents the amount of active electrical energy that is required to pump unit volume of water (Eq. 2).

$$\text{Specific Energy (MJ/m}^3) = \frac{\text{Pumping energy used (MJ/ha)}}{\text{Volume of water applied (m}^3/\text{ha)}} \quad (2)$$

Units of the indicator could be either of kWh, MJ or GJ per m^3 of water and electric consumptions were used for the analysis (Barbosa et al. 2018). Its inverse is called *intensity of energy-related water* usage or may be referred to as *water footprint of energy* (m^3/MJ).

Energy–crop (EC) Nexus performance indicator refers to amount of total input energy being consumed to produce a given amount of yield or the amount of yield obtained by a unit of total input energy. It is also called energy productivity (Eq. 3).

$$\text{Energy productivity (kg/MJ)} = \frac{\text{Amount yield obtained (kg/ha)}}{\text{Amount of energy consumed (MJ/ha)}} \quad (3)$$

Total input energy is the sum of energies sequestrated in the inputs being used for the production of the crops.

Crop–water (CW) Nexus is a water productivity or water use efficiency indicator which is calculated by dividing the amount of yield obtained to total amount of water applied per unit of harvested land (Eq. 4). The unit could be kg/m^3 or ton/m^3. The inverse is called Intensity of crop-related water usage or may also be referred to as water footprint of crop (Liu et al. 2019).

$$\text{Water productivity (kg/m}^3) = \frac{\text{Amount yield obtained (kg/ha)}}{\text{Amount of water applied (m}^3/\text{ha)}} \quad (4)$$

Composite indicator Performance evaluation of irrigated agriculture is complex because evaluation indexes and the results are different. The above six indicators describe isolated information rather than the interconnections between water, energy and crop resources. It is therefore necessary to use a composite indicator which ultimately be represented by a single value to compare the integrated performances of scheme categories. Such indicator is called water–energy–crop (WEF) nexus performance indicator.

Construction of composite index requires first normalizing of the original data and determination of weights for the normalized indicators. In this paper, the steps outlined in Kumar et al. (2021) and Zhang (2017) were adopted while constructing the composite indices.

The ultimate objective of constructing a composite index has been set in which maximization of water and energy productivities and minimization of water and energy consumptions, RIS, and specific energy. Next, a 6 by 11 hypothetical decision matrix based on the numbers of performance indicators ($n = 6$) and irrigation schemes ($m = 11$) was developed.

Data normalization was made to make the variables comparable by adjusting the scales (OECD 2008) as the indices have different units and dimensions. The min–max method was adopted as outlined in similar works such as OECD (2008), Dong et al. (2020), El-Gafy (2017), Liu et al. (2019), and Simpson et al. (2020). Among the six indicators, water and energy productivity indexes have positive attributes so Eq. (5) was applied. For the other indicators, Eq. (6) was used.

$$\text{Positive attributes;} \quad X_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (5)$$

$$\text{Negative attributes;} \quad X_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (6)$$

where x_{ij} is the value of the jth indicator for the ith irrigation scheme; $\max x_{ij}$ and $\min x_{ij}$ are the maximum and minimum values for the jth indicators, respectively;; X_{ij} is the normalized value of jth indicators for ith irrigation scheme.

Weights represent the trade-off across indicators (OECD 2008) and can be determined by subjective, objective or combinations of the two methods. The objective weight is based on intrinsic information of the data and it involves mathematical computations without any consideration of subjective preference.

Entropy, one of the objective weighting methods, is a measure of uncertainty and can be used to measure the quantity of useful information provided by data itself. The method has been widely used in many fields such as engineering, management and so on. It is associated with lack of information about the state and it is a very good scale when applied to different evaluation in decision making process (Dehdasht et al. 2020; Wu et al. 2011). On the other hand, authors such as El-Gafy (2017) applied equal weight method with the premises that the method is used to preserve multi-centric philosophy of WEF nexus approach such that each resource has equal importance (Allouche et al. 2015; Benson et al. 2015; Owen et al. 2018). In such cases, the normalized values can be used as final performance indices.

The authors believed that selected indicators for this study have differences on the information they contained so as their relative importance. Hence, each indicator has given weights based on entropy method. For comparisons and as supplemental information, however, results obtained from equal weight method were also included.

In information theory, entropy weight represents useful information of the evaluation index. The bigger the entropy weight of the index is the more useful information of the index is. It's the same in reverse. Entropy (E_j) of the j^{th} indicator was determined using Eqs. (7) to (8) (Dehdasht et al. 2020; Kumar et al. 2021; Wu et al. 2011; Zhang 2017);

$$E_j = -\frac{\sum_{i=1}^{m} f_{ij} \ln f_{ij}}{\ln m}, \quad (i = 1, 2, \ldots, m) \tag{7}$$

where

$$f_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}, \quad (i = 1, 2, \ldots, m) \tag{8}$$

If f_{ij} is all 0, then $f_{ij} \ln f_{ij}$ is also 0 in value.

After calculating entropy, the weight of each index was determined reflecting the importance of the index. The higher the usefulness value of one attribute, the greater its importance for evaluation and the bigger the attribute weight which depends on the difference between the information entropy of the attribute and 1 or $1-E_j$ (Hua et al. 2016; Zhang 2017). Weights of each of jth index were determined using Eq. (9) as described in Wu et al. (2011). Finally, calculated weights of the indicators were multiplied by respective normalized values and the composite indicators or WEFN indices (WEFNI) of each indicator were determined using Eq. (10).

$$w_j = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j}, \quad \sum_{j=1}^{n} w_j = 1, \ (j = 1, 2, .., n) \tag{9}$$

$$WEFNI = \frac{\sum_{j=1}^{n} w_j X_{ij}}{\sum_{j=1}^{n} w_j} = \sum_{j=1}^{n} w_j X_{ij}; \quad (i = 1, 2, \ldots, m; \ j = 1, 2, .., n) \tag{10}$$

where $w_j X_{ij}$ indicates weighted performance of the ith irrigation scheme on the jth indicator. All the other variables are already explained.

Results

Water and energy use and land productivities of individual schemes

Irrigation water use

Historical water application provides indications about water management practices of an irrigation schemes. Volume of water applied per unit of land depends on several factors such as crop type, climate of the area, irrigation intervals, availability of water, the irrigation system and physical conditions of the structures, water management practices etc. Except Kessem Gravity fed Surface scheme (KGS), the other ten irrigation schemes are located either in Metehara (4 schemes) or Wonji (six schemes) sugar factories.

Irrigation water applied (m^3/ha) by the studied sugarcane schemes for five consecutive years is presented in Fig. 2 which indicates existences of annual fluctuations. Most of the schemes applied highest water in the 2016/2017 production year for unknown reason. WGS applied the highest of all i.e., around 42,297 m^3/ha in 2016/2017 while DPD applied 9047 m^3/ha in 2018/2019 which is the lowest. The difference is more than four times.

Table 4 summarizes statistical values of 5 years observations. The results revealed that WGS with mean value of 38,510 m^3/ha was the most water consuming scheme followed by AGS (31,030 m^3/ha), MGS (30,940 m^3/ha), KGS (30,820 m^3/ha) and UGD (25,970 m^3/ha). WGS and DPC schemes applied the highest and the lowest. UGD is gravity fed sprinkler scheme but applied more water than all pump driven schemes and almost two times higher than the sprinkler schemes signifying direct relationships of pumping energy on the application of irrigation water.

The lowest variability was observed at WPS scheme of Wonji while the highest was at AGS of Metehara sugar factory. The former is pump driven surface scheme with the lowest pumping head while the second one is gravity fed surface scheme. In general, a decreasing pattern from gravity fed surface schemes to pump sprinklers was observed which is directly related with the energy required to apply the water.

Input energy use

Due to data limitations especially on land preparation operations, input rates of the year 2019/2020 were used. Seed cane, fertilizer and chemicals, irrigation water, machineries (tractors and implements), fuel and labor were the common energy sources for sugarcane production of the schemes while pumping electricity was additional source for pump driven schemes (Fig. 3). Except irrigation water and pumping energy, application and consumption rates of other inputs such as fertilizer, seed cane, fuel, labor were almost similar among the schemes.

The first five schemes use gravity force so that energy is not required for pumping the water. The graph in Fig. 3 begins to rise at WPS surface scheme towards DPD sprinkler scheme having the lowest and the highest pumping heads and the associated energies. The schemes had 5 and 74 m pressure heads with pumping energies of 6.99 and 104.87 GJ/ha, respectively.

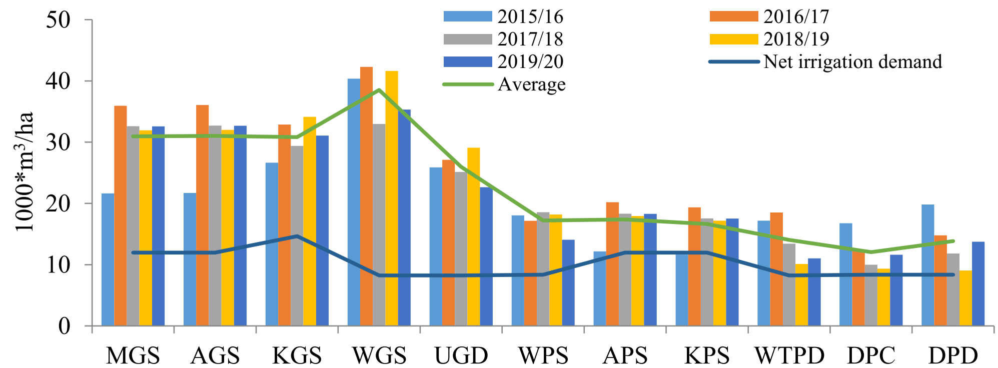

Fig. 2 The graph depicts 5 years historical and average water applied and mean net irrigation demands of the schemes under investigation. The abbreviations for names of the irrigation schemes are listed in Table 1

Table 4 Statistical summary of 5 years water use (1000*m^3/ha) of irrigation schemes

	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Mean	30.9	31.0	30.8	38.5	26.0	17.2	17.4	16.7	14.1	12.1	13.9
Max	36.0	36.1	34.1	42.3	29.1	18.6	20.2	19.3	18.5	16.8	19.8
Min	21.6	21.7	26.6	33.0	22.7	14.1	12.2	11.6	10.1	9.4	9.1
SD	5.4	5.5	3.0	4.1	2.4	1.8	3.1	2.9	3.7	2.9	4.0
Net irrigation demand	12.0	12.0	14.7	8.2	8.2	8.4	12.0	12.0	8.2	8.4	8.4

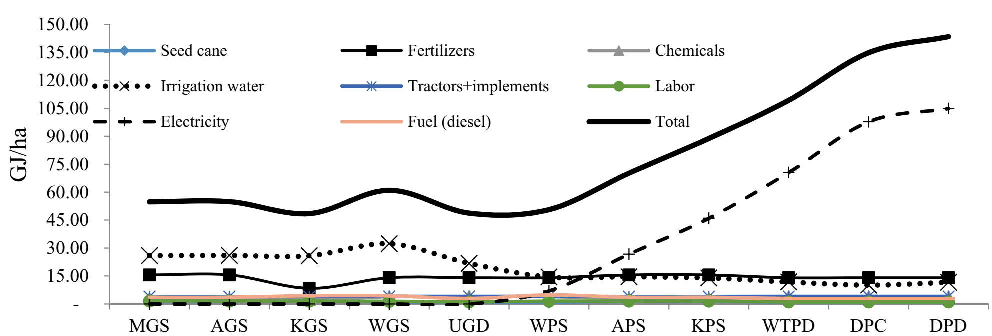

Fig. 3 Graphs for farm input energies being used for sugarcane production by irrigation schemes of Awash basin. Total input and pumping energy consumptions had similar pattern with pumping heads

Irrigation (pumping energy plus energy embedded in irrigation water) was the major energy consuming operation which constituted a minimum of about 42% up to the maximum of 80.1% total input energies of WPS and DPD schemes, respectively due to large differences of their pumping head.

Figure 4 presents the input energy share of the irrigation schemes in which irrigation water, fertilizer and electricity were the major energy sources. Irrigation water and fertilizer were the dominant energy sources for gravity surface schemes while the electricity was dominant for pump sprinklers. Contributions of the other inputs were not that much significant throughout the schemes compared to these three inputs. Both graphs, Figs. 3 and 4, demonstrate direct relationships of pumping energy with pumping head.

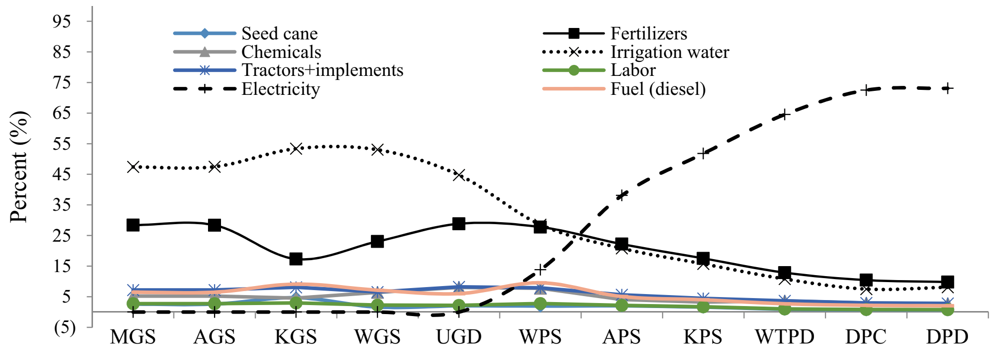

Fig. 4 Percentages of irrigation water and pumping energies of gravity surface and pump sprinkler schemes respectively are higher than other sources of input energies while proportion of fertilizer energy decreases towards the sprinkler schemes

Land productivity

It is the efficiency of input on output and non-declining crop productivity is an important indicator for measuring sustainable agriculture from an economic point of view (Zhen and Routray 2003).

Five years productivities of the schemes are shown in Fig. 5. Like irrigation water use neither increasing nor decreasing trend was observed but the data were oscillating. As shown in Figs. 2 and 5, the year 2016/17 was recognized for recording of highest volumes of water being applied and the lowest land productivities by most of the irrigation schemes.

The highest average productivity was recorded at WGS gravity surface scheme with 167.6 ton/ha (16.8 kg/m^2). It should be noted that that WGS applied the highest irrigation water (38,514.1 m^3/ha). The second and third highest average productivities were 148.6 and 134.0 ton/ha which belonged to AGS and MGS schemes (Table 5) by applying the second and third highest irrigation water i.e. 31,027.5 and 30,936.7 m^3/ha (Table 4), respectively.

Although an increase in energy use per hectare of land might be compensated by an increase in crop yield, our findings did not corroborate this. Despite the fact that conversion to sprinkler irrigation could alleviate pressures on water resources, performance of the sprinkler schemes compared to surface schemes were lower (more energy consumption but less productivity). According to Gosh and Chakma (2019), quantitative increase in agricultural inputs can multiply productivity but materialistic output is not always the determinant.

Grouping or categorizing of the irrigation schemes

It has been stated that water and energy consumptions of the irrigation schemes were related with pumping heads as exhibited in Figs. 2 and 3. The relationships of water applied, total input energy and productivities were statistically evaluated against total pressure heads. Figures 6 and 7 are results of total input energy and irrigation water applied against pumping heads and yields of the irrigation schemes, respectively.

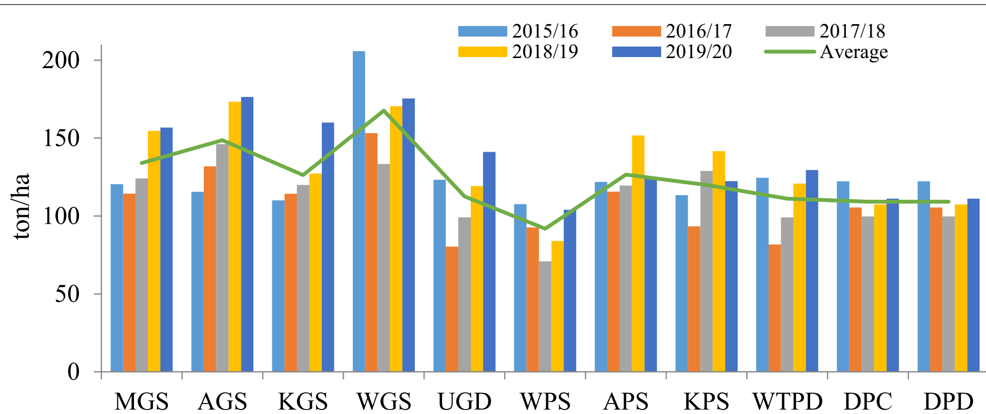

Fig. 5 Annual productivities (ton/ha of sugarcane) of irrigation schemes fluctuate except the first three gravity surface schemes

Table 5 Statistical summary of 5 years land productivities (ton/ha) of the irrigation schemes

	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Mean	134.0	148.6	126.3	167.6	112.6	91.8	126.6	119.9	111.1	109.2	109.2
Max	156.7	176.4	160.0	205.8	141.1	107.6	151.7	141.6	129.5	122.3	122.3
Min	114.3	115.5	110.1	133.4	80.3	70.9	115.6	93.4	81.7	99.7	99.7
SD	20.1	26.3	19.9	27.0	23.4	15.0	14.4	18.0	20.1	8.4	8.4

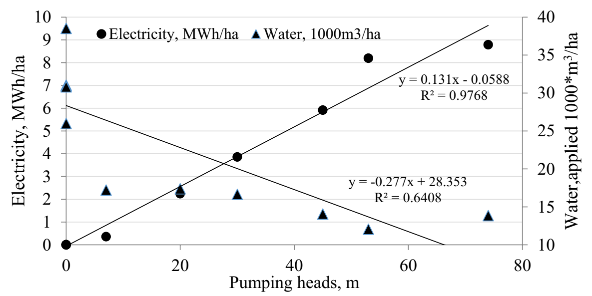

Fig. 6 Electrical energy consumption and water consumed as a function of pumping head in annual productivities (ton/ha) of irrigation schemes

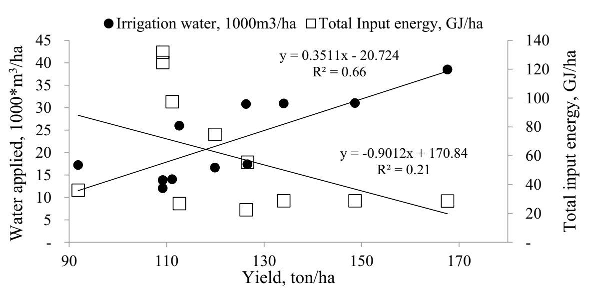

Fig. 7 Relationships of water applied and total input energy (excluding irrigation water) with yields of the irrigation schemes

Pumping energy and water applied had relationship with pressure heads in opposite directions with different magnitudes. As pressure head increases the amount of water decreases while pumping energy increases. Direct and best correlation ($R^2 = 0.98$) between pumping energy and head was found as indicated on Fig. 6. Good but negatively correlated relationships ($R^2 = 0.64$) was found between pressure head and total amount of water applied.

In Fig. 7 above water applied and sugarcane yield were positively related with good correlation ($R^2 = 0.66$). However, total input energy and yield were negatively related with weak correlation ($R^2 = 0.21$) indicating use of high energy particularly for water pumping did not bring yield advantages.

Figures 6 and 7 clearly confirmed that volume of water applied and total energy had strong correlation with pumping head which highly influenced resource use nature of the schemes. Accordingly, pressure heads can be used to categorize the irrigation schemes in the following manners; gravity surface schemes, pump driven surface schemes (pressure heads between 7 and 30 m) and pump sprinkler (pressure heads between 45 and 74 m).

In gravity surface schemes, water is conveyed and distributed through canals through gravity force. In pump surface schemes, water is pumped into main canals then conveyed and applied to the fields through gravity. Sprinklers use pump energy to abstract, distribute and apply the water. All schemes use surface water primarily rivers while electricity is the only source of energy for pumping the water.

In order to check existences of significant differences among the scheme categories on water and energy use, student t-tests together with LSD mean separation technique was made at 5% of significant level (Table 6).

Table 5 shows that, except land productivity, the differences among the different irrigation water application methods were statistically significant ($p < 0.05$).

Nexus performances of scheme categories

The following sections will focus on comparative assessment of the selected scheme categories based on six performance indicators i.e. water applied, total input energy, relative irrigation supply (RIS), water productivity, energy productivity and specific energy of pumping.

Water and total input energy consumptions

Water and input energy use of individual schemes were highlighted. Concepts of water and energy footprints make sustainability assessment more successful due to their ability to establish linkages with land (Gosh and Chakma 2019); hence, both indicators are included for assessing the scheme categories.

Figure 8a, b presents mean water applied and total input energies of the scheme categories. Mean water

Table 6 Mean Comparison of irrigation water application methods in terms of water productivity, total energy, energy productivity and energy efficiency

Categories	Number of schemes	Water (1000*m^3/ha)	Productivity (ton/ha)	Total energy (GJ/ha)	Energy productivity (kg/MJ)	Energy efficiency
Gravity surface	5	31.85^a	136.32^a	53.57^a	2.56^a	21.84^a
Pump surface	3	17.08^b	112.78^a	68.94^a	1.69^b	14.41^b
Sprinklers	3	13.32^c	109.84^a	129.17^b	0.86^c	7.35^c
P values		< 0.05	0.076	0.0024	0.00033	< 0.05

*The same letters indicate non-significant differences

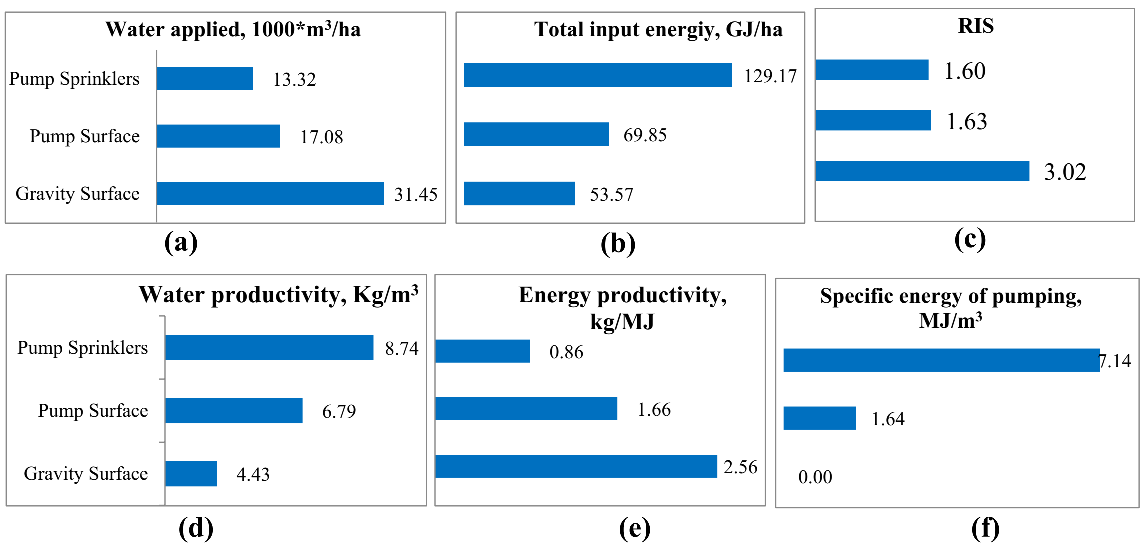

Fig. 8 Mean values of the six WEF nexus performance indicators of the scheme categories; **a** irrigation water applied in 1000 of m^3/ha; **b** total input energies in GJ/ha; **c** RIS (dimensionless); **d** water productivity in kg/m^3; **e** energy productivity in kg/MJ; and **f** specific energy of water pumping in MJ/m^3. Five years data were used

consumption of gravity schemes was 2.4 times higher than that of the sprinklers. Similarly, mean total input energy use of sprinklers was 2.4 times higher than that of gravity schemes. Water applied and total input energy of pump surface schemes were 1.3 times higher than sprinkler and gravity surface schemes, respectively. Water and total input energy usage of both gravity surface and sprinkler schemes were almost 1.8 times more than pump surface schemes.

Contributions of pumping energies for pump surface and sprinkler scheme categories were 35 and 71% of total input energies, respectively while it was zero for gravity surface. On the other hand, the contributions of irrigation water were 49, 22 and 9% of total energies of gravity surface, pump surface and sprinkler scheme categories, respectively.

Water–water nexus (RIS)

Water requirement is highly affected by the selected irrigation method (Daher and Mohtar 2015) which in turn governs the efficiency. Irrigation requirement is also affected by climatic conditions. Wonji, Metehara, and Kessem sugar factories are situated at different locations of Awash basin and irrigation schemes in these factories use different water abstraction and field application methods (Table 1). Average net irrigation demands and water applied per hectare are shown in Table 4. The values calculated using Eq. (1) are plotted in Fig. 8c.

RIS is more related to how well the supply matches the crop's requirements. Values less than 1 indicate deficit irrigation, and larger values show over irrigation. In practice, value around 1.2 is desirable to avoid deficit irrigation owing to on-farm distribution uniformity and imprecise irrigation scheduling (Rodríguez Díaz et al. 2011).

All scheme categories had RIS values above 1.2 and gravity surface schemes applied almost three times (RIS ≈ 3.02) more water than the crop demands. On the other hand, the values for the other two were almost equal (RIS of 1.6 and 1.63). Irrigation efficiency is the inverse of RIS (Molden et al. 1998) so that the respective values of gravity surface, pump surface and sprinkler schemes will be 33.1, 61.3 and 62.5% indicating poor performances of gravity surface and sprinkler schemes. Both had lower efficiencies than recommended standards.

Water–crop nexus

W*ater productivity* or *water use efficiency* was selected as an indicator (kg/m^3) because the index is influenced by the amount of water used and crop yield obtained. It has high correlation with infrastructural performance of the irrigation network, farm management techniques, and irrigation methods (Liu et al. 2019). The values calculated using Eq. (4) are plotted on Fig. 8d.

A particular category with higher water consumption will have less water productivity. Land productivity of gravity surface schemes was 26% higher than the sprinklers but consumed 135% more water which affected its water productivity. Water productivity of the sprinklers was two folds of gravity schemes. Although the scheme categories applied water in excess of net demands, the observed data revealed the tendency of direct relationships with land productivity which demanded further investigation.

Energy–crop nexus

Calculated energy productivity values based on Eq. (3) are plotted in Fig. 8e. Yield obtained per unit of total input energy (kg/MJ) is an indicator for energy–crop (EC) nexus.

A unit of total energy of gravity schemes produced almost 3 times more sugarcane than sprinklers and 1.5 times than pump surface schemes. Higher energy productivity shows more performance or use of less input energy. Surface schemes used lowest total input energy due to absence of pumping energy. If pumping energies of pump schemes were ignored, energy productivities of the pump surface and sprinklers would be 2.61 and 2.88 kg/MJ, respectively surpassing the gravity schemes.

Water–energy nexus

Indicators based on either total output or pumping energy can be used for water and energy nexus. Output energy produced per unit of irrigation water (MJ/m^3) is energy–water (EW) nexus used to measure the output energy per unit of water. However, total output energy is directly related with yield so that inclusion of the indicator might create 'double counting' because it has the same meaning with water productivity (kg/m^3). Hence, pumping energy used per unit of irrigation water (MJ/m^3) or *specific energy* which expresses the water–energy (WE) nexus was used for the analysis.

The values of specific energy calculated using Eq. (2) are plotted in Fig. 8f for pump driven surface and sprinkler schemes. The specific energy of gravity surface schemes is zero due to use of gravity force. On the other hand, sprinkler schemes consumed around 7.14 MJ of electric energy to pump one cubic meter of water which is almost 4.35 times higher than pump surface schemes.

Water–energy–crop nexus composite performance

The six indicators so far discussed might reveal superiority of a particular scheme category on others regarding either of water–water, water–crop, water–energy or energy–crop nexuses but will not enable us to identify integrated performances or WEF nexus. Water–energy–crop nexus Index (WEFNI) is used to assess the combined efficiency of energy and water in maximizing productivity by providing a picture to decision makers about performance of the WEF nexus management (El-Gafy 2017). Normalized values of the indicators for each irrigation scheme are presented in Table 7.

Sum of normalized values can be used as composite indices if allocation of equal weight is assumed. All the six indicators will have weight equal to 0.16667 (≈ 0.17) and when multiplied with normalized values, performance scores of the indicators will be obtained (Table 8). The maximum performance index was 0.17 while the minimum was zero attributed to high and low resource (water and energy) consuming schemes, respectively.

Performance indices of the scheme categories are presented in Table 9 by averaging values of schemes under the same category. Gravity surface schemes had highest input energy, specific energy and energy productivity but recorded the lowest water consumption, RIS, and water productivity performances while the opposites were true for sprinkler. In reality, specific energy of gravity schemes was zero with an index value of 0.17.

Higher WEFN index indicates better nexus performance. According to Nhamo et al. (2020b), WEF nexus composite indices for ranking resource use and performances are classified as unsustainable if indices range from 0 to 0.09; ranges from 0.1 to 0.2 are classified as low sustainable; 0.3–0.6 are moderately sustainable, and values in between 0.7 and 1 are highly sustainable. Attaining 1 is almost impossible. Accordingly, pump surface schemes had highest composite score followed by gravity surface schemes.

Table 7 Normalized values of the six indicators calculated for each irrigation scheme

Indicators	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Water applied	0.29	0.28	0.29	0.00	0.47	0.81	0.80	0.83	0.92	1.00	0.93
Input energy	0.93	0.93	1.00	0.87	1.00	0.98	0.77	0.58	0.36	0.09	0.00
RIS	0.64	0.63	0.78	0.00	0.46	0.80	0.98	1.00	0.90	0.99	0.92
Water productivity	0.06	0.14	0.00	0.05	0.05	0.25	0.65	0.63	0.85	1.00	0.81
Specific energy	1.00	1.00	1.00	1.00	1.00	0.95	0.80	0.66	0.40	0.00	0.04
Energy productivity	0.85	0.98	0.93	1.00	0.78	0.53	0.52	0.30	0.13	0.02	0.00
WEFNI	0.63	0.66	0.67	0.49	0.63	0.72	0.75	0.67	0.59	0.52	0.45

Table 8 Performance scores of the irrigation schemes

Indicators	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Water applied	0.05	0.05	0.05	0.00	0.08	0.13	0.13	0.14	0.15	0.17	0.16
Input energy	0.16	0.16	0.17	0.15	0.17	0.16	0.13	0.10	0.06	0.02	0.00
RIS	0.11	0.11	0.13	0.00	0.08	0.13	0.16	0.17	0.15	0.17	0.15
Water productivity	0.01	0.02	0.00	0.01	0.01	0.04	0.11	0.11	0.14	0.17	0.14
Specific energy	0.17	0.17	0.17	0.17	0.17	0.16	0.13	0.11	0.07	0.00	0.01
Energy productivity	0.14	0.16	0.16	0.17	0.13	0.09	0.09	0.05	0.02	0.00	0.00
WEFNI	0.63	0.66	0.67	0.49	0.63	0.72	0.75	0.67	0.59	0.52	0.45

Table 9 Average performance values of scheme categories after normalizing the indicators of each irrigation scheme based on equal weight method

Indicators	Gravity surface	Pump surface	Pump sprinklers
Water applied	0.04	0.14	0.16
Input energy	0.16	0.13	0.03
RIS	0.08	0.15	0.16
Water productivity	0.01	0.09	0.15
Specific energy (pumping)	0.17	0.13	0.02
Energy productivity	0.15	0.08	0.01
WEFN composite indices	0.61	0.71	0.52

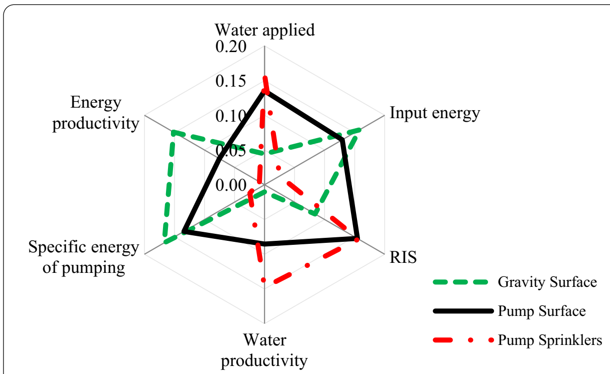

Fig. 9 Performance patterns of WEF nexus indicators based on equal weight method

Spider or web graphs (Fig. 9) are very helpful to visualize the interactions among the indicators and the imbalances on resource consumptions, to summarize results, to understand the main sustainability challenges and to identify opportunities for improvement in each category (Nhamo et al. 2020b). The further the distance of indices from the center, the more sustainable management while the closer to the center it is unsustainable.

Water applied and water productivities of gravity surface schemes and energy related indices of sprinklers schemes were skewed towards the center due to use of highest irrigation water and pumping energy, respectively. On the other hand, all indices of pump surface schemes were almost above the middle points. Despite having the highest composite index of 0.71, even resource utilization of pump surface schemes were unbalanced because of lower water and energy productivity performances. Achieving a circular shape would only indicate a balanced resource management but regarded as moderately sustainable if the composite score lies in between 0.3 and 0.6.

Performance indices of the indicators and composite scores calculated using Eqs. (7)–(9) or entropy method are presented in Table 10. The sum of the weights is 1.

Table 10 Performances indices of scheme categories calculated using entropy method

Indicators	Entropy, E_j	Weights, w_j	Performance values of scheme categories		
			Gravity surface	Pump surface	Pump sprinklers
Water applied	0.92	0.13	0.04	0.11	0.13
Input energy	0.92	0.14	0.13	0.10	0.02
RIS	0.95	0.08	0.04	0.08	0.08
Water productivity	0.81	0.31	0.02	0.16	0.27
Specific energy (pumping)	0.91	0.14	0.14	0.11	0.02
Energy productivity	0.88	0.20	0.18	0.09	0.01
WEFN indices		1.0	0.55	0.65	0.52

Water productivity had the lowest entropy but the highest relative weight followed by energy productivity. Relative weight of water productivity was doubled when compared to equal weighting method while weight of RIS was reduced by half. Under entropy method, importance of water and energy productivity indicators was increased while that of RIS was reduced. The combined importance of water and energy productivities weighs almost 50% of the six indicators.

The composite indices of gravity and pump surfaces were lowered almost by 10% compared to values calculated using equal weight method. As a result, all schemes categories were grouped under moderately sustainable performance. However, comparative nexus performances of the scheme categories remained the same.

Web graph of performance scores from entropy method is presented in Fig. 10. Water and energy productivity scores increased while other indices were skewed towards the center which is significant for RIS.

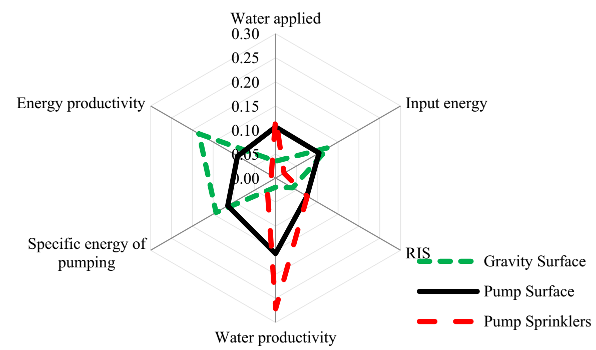

Fig. 10 Patterns of WEF nexus scores of scheme categories based on entropy weight method

In the spider graphs, pump surface schemes had relatively balanced resource management and moderately sustainable. A balanced resource management shows that resources are being developed and utilized holistically to achieve sustainability. Deformed shape of the web results from sectorial approach in resources utilization, development and management (Nhamo et al. 2020b), which is the current situation particularly for gravity surface and sprinkler schemes of the sugar factories. Improvements on water management for gravity schemes and energy use for sprinkler schemes were identified as key intervention strategies in the irrigation sector of the basin.

Discussion

High variability among the performance indices indicates not only unsustainable use of resources but also unbalanced use of the resources. Most of the sugarcane schemes applied highest water during the 2016/2017 production year. WGS (gravity fed surface scheme of Wonji factory) applied the highest of all in 2016/2017 while DPD (sprinkler scheme of the same factory) applied below a quarter of the highest amount during 2018/2019. Although both schemes are found in Wonji sugar factory for irrigating the same crop, irrigation technology could be the main reason for the difference. WGS is gravity fed surface while DPD is pump driven sprinkler scheme. Despite observing decreasing trend from gravity fed surface schemes towards pump driven sprinkler schemes, UGD gravity fed sprinkler scheme of Wonji factory consumed more water than any of pump drive surface schemes including Wonji Pump driven Surface scheme (WPS).

Like irrigation water usage, land productivities of the schemes were oscillating. The maximum and minimum productivities being recorded were 205.8 and 70.9 ton/ha (almost 3 folds) pertaining to WGS (in 2015/2016) and WPS (in 2017/2018) schemes of Wonji factory, respectively. Categorically, sprinkler schemes had lowest average productivity followed by pump driven surface and gravity fed surface schemes.

Energy embedded in irrigation water and pumping energy were major components of total input energies.

Pumping energy is also governed by the amount of water applied and the associated pressure heads. The lowest and highest pumping energies were attributed to WPS (pump driven surface scheme) and DPD (Dodota dragline sprinkler) scheme having total pressure heads of 5 and 74 m, respectively. Both schemes are part of Wonji factory and use river water while the former applied 25% more water than the latter one.

In general, irrespective of water application methods or technologies, the recorded annual water usage and land productivity were inconsistent. Moreover, although irrigation scheme particularly both gravity and pump driven surface schemes applied excess water, their productivities were higher than that of sprinklers.

The reason for such tradeoffs could arise from the design (high pressure heads) or from poor scheme management (applying excess water). The sprinklers consumed high electric energy to pump irrigation water. Gravity schemes used excess water. Excessive water use causes both extravagant of water and energy. Low irrigation efficiencies are results of applying excess water than crop demands which lead to problems such as water logging and salinity, loss of soil fertility and decline in productivity. Moreover, applications of excess water will consume more energy if pumps are used. Reducing the amount of water applied will improve water productivity and at the same time safeguarding the energy consumption. For effective water saving, however, measures to improve water productivity needs to align with limits on water use. Failure to meter and strictly monitor the water bound to increase the amount of water applied.

Water efficient irrigation systems are generally more energy intensive than water inefficient systems. The most effective water efficiency measure involves changing from open to closed delivery systems. For example, installing of sprinklers by replacing gravity fed surface systems entail additional energy. Results of the study in some sense support these facts. Adoption of modern irrigation will not always improve the nexus performances of the production system. The improvement of water productivity was gained from the introduction of pressurized irrigation systems into the basin which in turn was overshadowed by high energy consumptions.

According to Dong et al (2020), many factors affect efficiency of irrigation water use which are related to the natural conditions of irrigation area, irrigation system used, level of economic development, personnel management, crop type, the local environment, and many other factors (Dong et al. 2020).

Synergistic use of water, energy and food should be defined in a context-specific way for different regions according to their development priorities (Liu et al. 2017). Sugar factories are expected to be energy self-sufficient and support national demand due to high energy sequestrated in the crop. Use of cane straws, for example, as a source of energy and manure will guarantee local availability of energy and the imported chemical fertilizers for the irrigated production system. Straws as energy source can generate enough electricity for pumping irrigation water currently supplied from the national grid. Such approaches create a plausible synergy among water, energy and food sectors which enable co-benefit scenario for the sugarcane production system.

Local energy generation is pieces of the solutions. It should be supplemented with efficient utilization through use of innovative farm operations and production systems which can also be used for gravity surface schemes by upgrading the systems. There is still much room to improve efficiency of WEF nexus in irrigation schemes of Awash basin. For such improvements, however, clear and accepted water and energy allocation rules coupled with strong institutions and technical capacity are imperative.

Conclusion

WEF nexus is a useful conceptual framework developed to understand complex interactions of water, energy and crop resources. The approach has enabled evaluation of resource utilization synergies and trade-offs of sugarcane producing schemes through selected indicators and indices.

Eleven sugarcane producing irrigation schemes of Wonji, Metehara and Kessem sugar factories in Awash basin and six resource use performance indicators have been utilized for comparison purposes with the context of WEF nexus. The irrigation schemes were grouped into three categories based on their water pumping heads i.e. gravity surface schemes with zero pumping heads, pump surface schemes with pumping heads of 5–30 m and sprinklers with pumping heads of 45–74 m. The categorization was carried out based on in depth investigation of individual schemes supplemented by statistical analysis.

Historical data regarding water applied, input energies including pumping energy and land productivities of the irrigation schemes were collected from the sugar factories. Based on the data natures, six performance indicators were selected which are water use, total input energy, RIS, water productivity, energy productivity and specific energy including their overall performance indicator or WEFN index were applied while comparing the three categorized schemes. Performance scores of the indicators were determined using both equal weight and entropy methods after normalizing through min–max method.

The selected indicators have the capacity to integrate various measures into an index and are useful tools for measuring sustainability and will help to predict changes that can be corrected by management and provide information about the future development. They were quantitatively represented or with numerical values and mathematically integrated to produce a value for sustainability.

In the sugar factories of Ethiopia, there is an evident for over emphasis on crop productivity at the expense of energy and water resources. However, neither of the resources has been properly managed. Results showed that there was a general trend of increasing energy consumption with increasing water use which was witnessed in irrigation sector of Awash basin where conversions were made from gravity to pressurized methods. Reductions in water consumptions were attained but there was an increase in energy consumption.

The sugar factories are expected to cover their factory and pumping energy demands. Some of the factories such as Wonji are unable to supply energy even for the factory. All pump driven irrigation schemes of Wonji and Metehara use electricity from the national grid.

Regarding the comparative assessments, gravity surface schemes had the highest total input energy and energy productivity scores while pump sprinkler schemes had the highest scores on indicators related to irrigation water such as water applied, RIS and water productivity. Pump surface schemes were in the middle. Results of the WEF nexus or composite indicators revealed a different story. Pump surface schemes scored the highest followed with gravity surface schemes while that of the sprinkler schemes performed the least based on the composite WEFN index.

For a balanced and sustainable resource development, utilization and management, it should target to make all sectors reach the highest index in water productivity of 0.27 achieved by sprinkler schemes and attain a circular shape in the spider graph; otherwise, the current approach will continue creating an imbalances. Such imbalances have been created due to unscientific use of irrigation water and energy without improvements of the outputs. In all of the studied schemes proper water management practices are critical issues. The basin is highly dependent on irrigated agriculture and the information generated will help the water management institutions for informed decision making. There is still a large room for improvement of energy and water productivities in all studied schemes indicating improvements of scheme operations to enhance water and energy management are an essential elements of the basin.

Abbreviations

AGS: Abadir gravity surface; APS: Abadir pump surface; DPC: Dodota pump center pivot; DPD: Dodota pump dragline; KGS: Kessem gravity surface; KPS: Kenifa pump surface; MGS: Merti gravity surface; RIS: Relative irrigation supply; UGD: Ulaga gravity dragline; WEF: Water, energy, and food; WEFN: Water, energy, and food nexus; WEFNI: Water, energy, and food nexus index; WGS: Wellenchiti gravity surface; WPS: Wonji pump surface; WTPD: Wake Tiyo pump dragline.

Acknowledgements

The authors highly appreciate reviewers of this article

Author contributions

Y.K. contributed on acquisition, collection, analyses and interpretation of data and also on drafting of the report. Both B.B. and T.A. contributed on checking data qualities, revising the drafts, the analyses methods, integrity of the paper and finally read and approved this manuscript. All authors read and approved the final manuscript.

Funding

The research was not funded by any organization.

Availability of data and materials

The datasets used for the study are not publicly available due to privacy of the sugar factories.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Addis Ababa Institute of Technology (AAiT), Addis Ababa, Ethiopia. [2]Civil and Environmental Engineering Department, Addis Ababa Institute of Technology (AAiT), Addis Ababa, Ethiopia. [3]Water and Land Research Center, Addis Ababa, Ethiopia.

Received: 24 June 2022 Accepted: 2 September 2022
Published online: 24 September 2022

References

Ahmad A, Khan S (2009) On comparison of water and energy productivities in pressurized irrigation systems. In: 18th World IMACS/MODSIM Congress, Cairns, Australia 13–17 July 2009. http://mssanz.org.au/modsim09

Allouche J, Middleton C, Gyawali D (2015) Technical veil, hidden politics: interrogating the power linkages behind the nexus. Water Alternat Interdiscipl J Water Polit Dev 8:610–626

AwBA (2018) Awash River Basin Atlas. Awash Basin Authority (AwBA). Addis Ababa, Ethiopia

Awulachew SB, Yilma AD, Loulseged M, Loiskandl W, Ayana M, Alamirew T (2007) Water resources and irrigation development in Ethiopia. Working paper 123. International Water Management Institute, Colombo, Sri Lanka

Barbosa, Brenon DS, Colombo A, de Souza JGN, da S Baptista VB, de Araújo ACS (2018) Energy efficiency of a center pivot irrigation system. J Braz Assoc Agric Eng 38(2):284–292

Bekele Y, Nata T, Bheemalingswara K (2012) Preliminary study on the impact of water quality and irrigation practices on soil salinity and crop production. Gergera Watershed Atsbi-Wonberta Tigray Northern Ethiopia MEJS 4(1):29–46

Benson D, Gain AK, Rouillard JJ (2015) Water governance in a comparative perspective: from IWRM to a "nexus" approach? Water Alternat Interdiscipl J Water Polit Dev 8:756–773

Birhanu H (2011) Effect of deficit irrigation application on yield of sprinkler irrigated sugarcane at Finchaa Sugar Estate, Horro Guduru Wollega. Master Thesis. Haramaya University, Ethiopia

Bizikova L, Roy D, Swanson D, Venema HD, McCandless M (2013) The water–energy–food security nexus: towards a practical planning

and decision-support framework for landscape investment and risk management. IISD REPORT. The International Institute for Sustainable Development
Chamsing A, Salokhe V, Singh G (2006) Energy consumption analysis for selected crops in different regions of Thailand. Agricultural Engineering International: the CIGR Ejournal. Manuscript EE 06 013, vol VIII
Chapagain AK, Hoekstra AY, Savenije HHG, Gautam R (2006) The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in cotton producing countries. Ecol Econ 60:186–203. https://doi.org/10.1016/j.ecolecon.2005.11.027
Daccache A, Ciurana JS, Rodriguez Diaz JA, Knox JW (2014) Water and energy footprint of irrigated agriculture in the Mediterranean region. Environ Res Lett 9(2014):124014
Daher BT, Mohtar RH (2015) Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Int 40:748–771
Dehdasht G, Ferwati MS, Zin RM, Abidin NZ (2020) A hybrid approach using entropy and TOPSIS to select key drivers for a successful and sustainable lean construction implementation. PLoS One 15(2):e0228746. https://doi.org/10.1371/journal.pone.0228746
Dong L, Zhou L, Li H, Fu Q, Li M, Muhammad AF, Shoaib A, Li T, Muhammad IK (2020) Optimization of irrigation water use efficiency evaluation indicators based on DPSIR-ISD model. Water Supply. https://doi.org/10.2166/ws.2019.135
El-Gafy I (2017) Water–food–energy nexus index: analysis of water–energy–food nexus of crop's production system applying the indicators approach. Appl Water Sci. https://doi.org/10.1007/s13201-017-0551-3
Ethiopian Electric Power (2015) Power Demand Forecast (unpublished report). Addis Abeba
Fabiani S, Nino P, Vanino S (2016) Guidelines for on farm water–energy–food audit, including training material. Vo2. WP4.1–water–energy–food nexus; farming tools for external nutrient inputs and water Management project. FATIMA Consortium, 2015
Gebremeskel T, Mekonen A (2015) Evaluation of the effects of current irrigation water pricing systems on water productivity in Awash river basin, Ethiopia. Afr J Agric Res 10(14):1789–1795. https://doi.org/10.5897/AJAR2013.7541.ISSN1991-637X
Ghosh B, Chakma N (2019) Composite indicator of land, water and energy for measuring agricultural sustainability at micro level, Barddhaman District, West Bengal, India. Ecol Indic 102(2019):21–32. https://doi.org/10.1016/j.ecolind.2019.02.011
Gómez-Limón JA, Riesgo L (2008) Alternative approaches on constructing a composite indicator to measure agricultural sustainability. Paper presented on the 107th EAAE Seminar. Modelling of Agricultural and Rural Development Policies. Sevilla, Spain, January 29th–February 1st, 2008
Gundogmus E (2006) Energy use on organic farming: a comparative analysis on organic versus conventional apricot production on small holdings in Turkey. Energy Convers Manag 47:3351–3359
Haile GG, Kassa AK (2015) Irrigation in Ethiopia: a review. Acad J Agric Res 3(10):264–269. https://doi.org/10.15413/ajar.2015.0141.ISSN:2315-7739
Hua Y, Jiang H, Ma S, Zhang D, Ma J (2016) Integrated model of assisted parking system and performance evaluation with entropy weight extended analytic hierarchy process and two-tuple linguistic information. Adv Mech Eng 8(7):1–14. https://doi.org/10.1177/1687814016654635
Jackson T (2009) An appraisal of the on-farm water and energy nexus in irrigated agriculture. Dissertation, Charles Sturt University. Australia
Karimi M, Rajabi Pour A, Tabatabaeefar A, Borghei A (2008) Energy analysis of sugarcane production in plant farms: a case study in Debel Khazai agro-industry in Iran. Am-Euras. J Agric Environ Sci 4(2):165–171
Kedir Y (2021) The stumbling irrigation sector of Ethiopia: critical review and analysis. Irrig Drainage Sys Eng 10:257
Kedir Y, Berhanu B, Alamirew T (2021) Comparative efficiency analysis of irrigation scheme categories of Awash River Basin, Ethiopia. J Resour Dev Manag 79(03):21–35. https://doi.org/10.7176/JRDM/79-03
Kitani O (1999) CIGR handbook of agricultural engineering. Volume V: Energy & Biomass Engineering. St Joseph, USA: American Society of Agricultural Engineers, 19
Kumar R, Singh S, Bilga PS, Jasveer Singh J, Singh J, Maria-Luminit S, Pruncu CI (2021) Revealing the benefits of entropy weights method for multi-objective optimization in machining operations: a critical review. J Mater Res Technol 10:1471–1492. https://doi.org/10.1016/j.jmrt.2020.12.114
Liu J, Yang H, Cudennec C, Gain AK, Hoff H, Lawford R, Qi J, de Strasser L, Yillia PT, Zheng C (2017) Challenges in operationalizing the water–energy–food nexus. Hydrol Sci J. https://doi.org/10.1080/02626667.2017.1353695
Liu C, Zhang Z, Liu S, Liu Q, Feng B, Tanzer J (2019) Evaluating agricultural sustainability based on the water–energy–food nexus in the Chencmengquan irrigation district of China. Sustainability 11:5350. https://doi.org/10.3390/su11195350
Mabhaudhi T, Nhamo L, Mpandeli S, Nhemachena C, Senzanje A, Sobratee N, Chivenge PP, Slotow R, Naidoo D, Liphadzi S, Modi AT (2019) The water–energy–food nexus as a tool to transform rural livelihoods and well-being in southern Africa. Int J Environ Res Public Health 16:2970. https://doi.org/10.3390/ijerph16162970
McGrane SJ, Acuto M, Artioli F, Chen P-Y, Comber R, Cottee J, Farr-Wharton G, Green N, Helfgott A, Larcom S, McCann JA, O'Reilly P, Salmoral G, Scott M, Todman LC, van Gevelt T, Yan X (2018) Scaling the nexus: towards integrated frameworks for analyzing water, energy and food. Geogr J 2019(185):419–431. https://doi.org/10.1111/geoj.12256
Molden D, Sakthivadivel R, Perry CJ, de Fraiture C, Kloezen WH (1998) Indicators for comparing performance of irrigated agricultural systems. IWMI Research Report 20
Nhamo L, Ndlela B, Mpandeli S, Mabhaudhi T (2020) The water–energy–food nexus as an adaptation strategy for achieving sustainable livelihoods at a local level. Sustainability 12:8582. https://doi.org/10.3390/su12208582
Nhamo L, Mabhaudhi T, Mpandeli S, Nhemachena C, Senzanje A, Naidoo D, Liphadzi S, Modi AT (2020) Sustainability indicators and indices for the water–energy–food nexus for performance assessment: WEF nexus in practice, South Africa case study. Environ Sci Policy 109:15–24. https://doi.org/10.1016/j.envsci.2020.04.010
Nie Y, Avraamidou S, XinXiao EN, Pistikopoulos JL, Zeng Y, Song F (2019) A food–energy–water nexus approach for land use optimization. Sci Total Environ 659(2019):7–19. https://doi.org/10.1016/j.scitotenv.2018.12.242
OECD (2008) Handbook on constructing composite indicators: methodology and user guide. Organization for Economic Co-operation and Development. OECD Publishing, Paris
Owen A, Scott K, Barrett J (2018) Identifying critical supply chains and final products: an input–output approach to exploring the energy–water–food nexus. Appl Energy 210:632–642. https://doi.org/10.1016/j.apenergy.2017.09.069
Planning and Development Commission (2021) Ten years development plan; a pathway to prosperity 2021–2030. Federal Democratic Republic of Ethiopia, Addis Abeba
Purwanto A, Sušnik J, Suryadi FX, de Fraiture C (2021) Water–energy–food nexus: critical review, practical applications, and prospects for future research. Sustainability 13:1919. https://doi.org/10.3390/su13041919
Rodríguez Díaz JA, Camacho Poyato E, Blanco Pérez M (2011) Evaluation of water and energy use in pressurized irrigation networks in southern Spain. J Irrig Drainage Eng. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000338
Sadeghi SH, Moghadam ESh, Delavar M, Zarghami M (2020) (2020) Application of water–energy–food nexus approach for designating optimal agricultural management pattern at a watershed scale. Agric Water Manag 233:106071. https://doi.org/10.1016/j.agwat.2020.106071
Siala F, Al-Soof N, Mazraati M (2017) The energy–water–food nexus: managing key resources for sustainable development. OFID Pamphlet Series 41. Vienna, Austria
Silalertruksa T, Gheewala S (2018) Land–water–energy nexus of sugarcane production in Thailand. J Clean Prod 182:521–528. https://doi.org/10.1016/j.jclepro.2018.02.085
Simpson GB, Jewitt GPW, Badenhorst J (2020) The water–energy–food nexus index and its application to South Africa and the Southern African Development Community. WRC Report no. 2959/1/19, Water Research Commission, Pretoria. ISBN No 978-0-6392-0113-9. http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/2959_final.pdf
Singh S, Mittal JP (1992) Energy in production agriculture. Mittal Publications, India
Vergara JC, Rojas G, Ortegon K (2020) Sugarcane straw recovery for bioenergy generation: a case of an organic farm in Colombia. ACS Omega 5:950–7955. https://doi.org/10.1021/acsomega.9b04340

Wakil M, Umar SS, Abubakar I, Zubairu M (2018) Energy-use efficiency of rice production under irrigation in Jere Bowl Borno State, Nigeria. Am J Environ Resource Econ 3(1):6–11. https://doi.org/10.11648/j.ajere.20180301.12
Wasihun GH, Silalertruksa Th, Gheewala SH, Jakrawatana N (2019) Water–energy–food nexus of sugarcane production in Ethiopia. Environ Eng Sci. https://doi.org/10.1089/ees.2018.0549
Wu J, Sun J, Liang L, Zha Y (2011) Determination of weights for ultimate cross efficiency using Shannon entropy. Expert Syst Appl 38(2011):5162–5165. https://doi.org/10.1016/j.eswa.2010.10.046
Yavuz D, Topaz R, Yavuz N (2014) Determining energy consumption of sprinkler irrigation for different crops in Konya Plain. Turk J Agric Nat Sci 1(3):312–321
Yibeltal T (2013) Synthesis report: Awash River basin water audit, Addis Ababa, Ethiopia: Project "Coping with Water Scarcity-Developing a National Water Audit with emphasis on agricultural water management". United Nations Food and Agriculture Organization (FAO) and Federal Democratic Republic of Ethiopia
Yuan KYu, Lin Y-C, Chiueh P-T, Lo S-L (2018) Spatial optimization of the food, energy, and water nexus: a life cycle assessment-based approach. Energy Policy 119(2018):502–514. https://doi.org/10.1016/j.enpol.2018.05.009
Zahedi M, Mondani F, Reza H (2015) Analyzing the energy balances of double cropped cereals in an arid region. Energy Rep 1:43–49
Zhang J (2017) Application of entropy weight method in the evaluation of the smart growth. Advances in engineering research, vol. 114. International Conference on Advances in Materials, Machinery, Electrical Engineering (AMMEE 2017). http://creativecommons.org/licenses/by-nc/4.0/
Zhen L, Routray JK (2003) Operational indicators for measuring agricultural sustainability in developing countries. Environ Manage 32(1):34–46. https://doi.org/10.1007/s00267-003-2881-1

Publisher's Note