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REVIEW ARTICLE

Water-energy-environment nexus for global food security and ecosystem sustainability-insight from energy budgeting, optimization and artificial intelligence

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Abstract

Water, energy and environment are inextricably linked, and exhibit a close nexus with crop production, ecosystem sustainability and food security. Chemical fertilizers and irrigation water were the major hot spots of water and energy footprints, with significant impact on carbon (C) footprints that largely impacts ecosystem sustainability. The non-renewable energy (NRE) shared ~ 59–92%, while renewable energy (RE) comprised ~ 8–41% of total energy input (E_I) in field crops. The direct energy (DE) and indirect energy (IDE) sources comprised ~ 10–74% and 26–90% of E_I, respectively. In vegetable and fruit crops, the RE and NRE shared ~ 1.4–24% and 76–98.6%, whilst the DE and IDE sources shared ~ 14–90% and 10–86% of E_I. The energy ratio varied between 1.49–5.00 for rice, 1.75–7.50 for wheat, 3.80–7.41 for maize and 0.70–4.80 for cotton ecosystems. The corresponding specific energy ranged between 6.4–16.7, 4.0–8.42, 3.80–6.93 and 4.99–19.2 MJ kg^{-1}, respectively. The greenhouse gases emission in crop production was related linearly to E_I in crop production and was substantially decreased under optimized production situations. The study highlights the need of intensified agricultural extension efforts to disseminate the robust technological interventions for resource use optimization for decreased energy and C footprints in crop production for long-term system sustainability. The artificial neural networks and adaptive-neuro fuzzy inference system of variable complexity viz. single and multi-layered sub-networks developed for various crops in different agro-ecological regions could be highly helpful to the researchers and policymakers for designing future strategies for enhancing ecosystems' resilience and environmental sustainability.

Keywords Energy use efficiency · Renewable and non-renewable energy · Direct energy · Crop production · Carbon footprints

Introduction

The relationship between water, energy and the environment is crucial for promoting sustainable crop production, which in turn plays a critical role in ensuring global food security and ecosystem sustainability (Esengun et al. 2007; Kaur et al. 2024). This interdependent relationship, known as the 'water-energy-environment nexus' highlights the importance of managing these resources in a sustainable manner to ensure the long-term viability of agricultural production, while minimizing environmental impact (Esengun et al. 2007; Pishgar-Komleh et al. 2011; Singh et al. 2020, 2021a, b, c). This nexus is characterized by intricate and interdependent relationships that have far-reaching implications for ecosystem sustainability, human well-being and the progress of civilization (Fig. 1). These connections are multifaceted and complex, underscoring the critical importance of managing these resources sustainably to ensure their continued availability and minimizing any adverse impacts on the environment (Singh et al. 2020). The agricultural ecosystem serves a dual purpose, acting both as a consumer and producer of energy in the form of bio-energy. Through the process of photosynthesis, solar energy is converted and transferred into food, feed and fiber energy, resulting in a continual cycle of energy conversion within the ecosystem (Alam et al. 2005). With considering continuous growth in world's population, the contribution of agriculture to greenhouse gases (GHGs) emissions is of great concern. As

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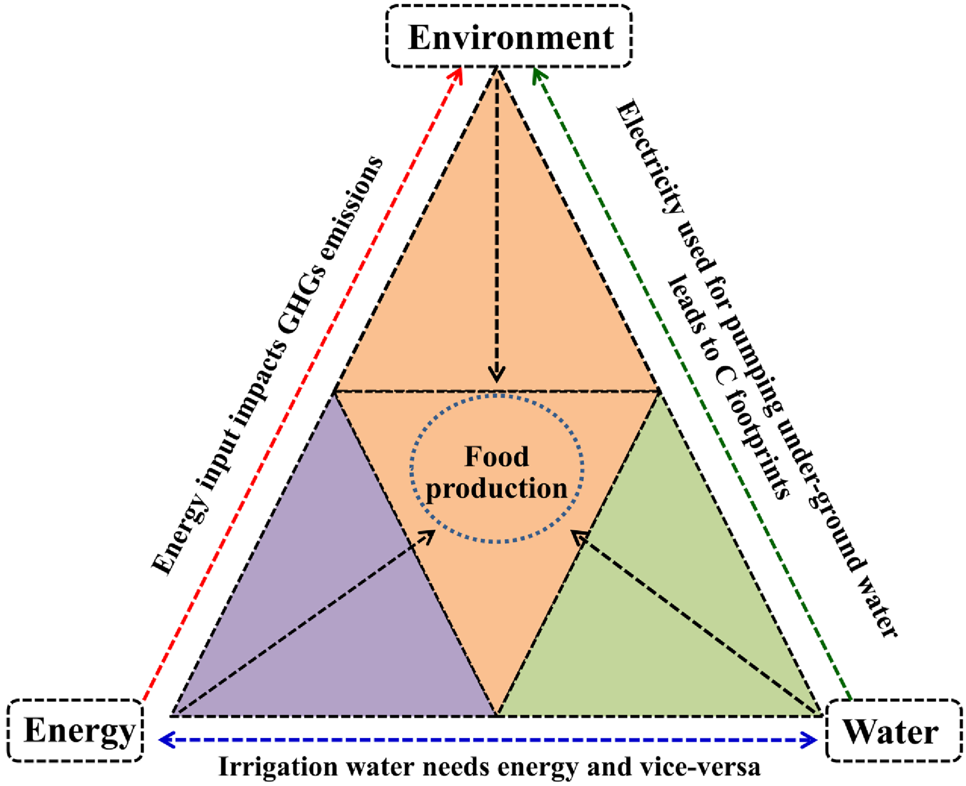

Fig. 1 Water-energy-environment nexus for crop production

such, it is increasingly important to address and mitigate the impact of agricultural activities on GHGs emissions (Vetter et al. 2017). Given the challenges posed by a rapidly globalizing economy and increasing socio-economic pressures, the sustainable management of water and energy resources is of utmost importance for ensuring food security (Bhatt et al. 2023). The resilience of agricultural ecosystems depends upon sustainable management practices that balance the utilization and availability of natural resources. To this end, the sustainable agricultural goals aim to establish innovative linkages between farm tools and ecosystem services to optimize the use of inputs, including water, nutrients and energy, while prioritizing environmental and social security, safety, and clean crop productivity. One of the primary concerns for sustainable crop production is achieving optimal yields with reduced inputs, thereby increasing farm income, while also conserving the environment (Singh et al. 2019a, 2021a, b, c).

It is expected that the world's population would surpass ~ 9 billion by the year 2050 (CTA-CCAFS 2011). Global projections indicate that food production will need to increase by c.a. 70% to meet the growing demand for food associated with the increasing global population. (CTA-CCAFS 2011), and the situation would increase the vulnerability of food security (Koohafkan and Stewart 2008). The impact of this situation is expected to be particularly severe for the overgrowing human population in developing nations. Currently, ~ 75% of the world's poor reside in rural areas (Nelson et al. 2009). World food prices, which are often seen as a barometer of the future of agriculture, are on the rise. This trend suggests the presence of supply and demand imbalances in the face of growing resource scarcity (Nelson et al. 2010). In response to this pressure, the uses of energy in agriculture has become increasingly important, particularly as the amount of arable land available remains limited and as people aspire to higher standards of living.

Indeed, all agricultural operations from field preparation to harvesting and threshing, require some form of energy (Pishgar-Komleh et al. 2012; Khoshnevisan et al. 2013a; Nabavi-Pelesaraei et al. 2016; Singh et al. 2019a,b). While increased energy input can lead to higher crop yields, it may not always translate into maximum profits, as the costs associated with increased production can also rise (Erdal et al. 2007). Therefore, achieving maximum crop productivity, while optimizing energy input require a careful assessment of the interactions between chemical fertilizers, irrigation, and tillage operations, all of which can contribute towards increased on-farm energy consumption (Billore et al. 1994; Shahan et al. 2008). Studies examining the relationship between energy use and yield maximization have shown that while enhanced energy input can increase crop yields to a certain extent, yields eventually decline beyond a certain point (AghaAlikhani et al. 2013). In general, agricultural production tends to have a net energy balance, with lower energy inputs and higher energy outputs (Shahan et al. 2008). However, higher energy inputs can result in reduced energy use efficiency (also known as energy ratio; E_R) and energy productivity (E_P) (Billore et al. 1994) and increased GHGs emissions (Pishgar-Komleh et al. 2012; Khoshnevisan et al. 2013a; Sarauskis et al. 2014; Singh and Benbi 2020a) that significantly impacts C sustainability of the cropland ecosystems (Singh et al. 2020; Singh and Benbi 2020b). Management practices that exhibit a greater difference between energy input and output tend to result in higher net energy gain (NEG) and E_R (Uhlin 1998; Tzanakakis et al. 2012; Singh and Benbi 2020a, b). Energy input–output analyses are commonly used to assess E_R and evaluate the environmental implications of inefficient energy consumption (Mandal et al. 2002; Singh et al. 2019a, b; Singh et al. 2020).

The agricultural sector relies heavily on fossil and other non-renewable energy (NRE) resources, which are becoming increasingly scarce. Fossil fuels, in particular, are expected to be depleted by the end of the century. Moreover, the use of NRE sources has always been expensive, and can have serious technological and environmental implications such as air pollution, acid rain, and most importantly, global climate change resulting from GHGs emissions from fossil fuel combustion (Boyle 2004). Therefore, understanding the objective and developmental stages of the energy-water-environment nexus is important to grasp its evolution. However, there is a need for clarity regarding available data from various studies carried out in different production contexts. The findings of this review can be valuable to policymakers and stakeholders in realizing the significance of the energy-water-environment nexus and implementing policies for disseminating efficient interventions to ensure long-term sustainability of ecosystems, while reducing reliance on fossil fuels and minimizing carbon dioxide equivalent (CO_{2e}) emissions. The review is structured into different sections, discussing progress towards the review objectives and analyzing various scenarios, and concluding with overall findings.

Energy flow due to water use in crop production

The USA has the highest gross virtual water export of around 314 Gm^3 $year^{-1}$, followed by China (143), India (125), Brazil (112), Argentina (98), Canada (91), Australia (89), Indonesia (72), France (65) and Germany (64 Gm^3 $year^{-1}$) (Hoekstra and Mekonnen, 2007). The countries with the largest gross virtual water imports were the USA (234 Gm^3 $year^{-1}$), Japan (127), Germany (125), China (121), Italy (101), Mexico (92), France (78), the United Kingdom (77), and The Netherlands (71 Gm^3 $year^{-1}$) (Hoekstra and Mekonnen, 2007). Worldwide, the annual extraction of groundwater is estimated to be > 650 km^3, with around 75% of this volume being extracted in India, the United States, China, Pakistan, Iran, Mexico, and Saudi Arabia combined (Giordano 2009). India, the world's largest groundwater user (Aeschbach-Hertig and Gleeson 2012), withdraws ~ 230 billion m^3 groundwater annually (Mishra et al. 2018), which is the lifeline of millions of people in the country (Kulkarni et al. 2015). Groundwater depletion assessed using a global map revealed those areas such as north-western India, north-eastern China, north-eastern Pakistan, and California's Central Valley aquifers in the USA were the main hotspots (Wada et al. 2010). Significant groundwater depletion has beeen observed in Iran, central Yemen, and southern Spain (Wada et al. 2010; Werner et al. 2013). Over the past century, around 700–800 km^3 of groundwater is depleted from aquifers in the USA (Konikow and Kendy 2005). During the period of 1967–2000, the surface water in the Fuyang River Basin located in the North China Plain region experienced a decline of 8–50 m (Shah et al. 2004). Similarly, around 143.6 km^3 of groundwater has been depleted between 2003 and 2009 in north-central Middle East, which includes parts of the Tigris and Euphrates River Basins and western Iran (Voss et al. 2013). Water and energy are inextricably linked (Healy et al. 2015; Iseman and Tidwell 2015), but often remains largely absent in planning and operation (Hoff 2011). Electricity generation necessitates water usage either directly or indirectly throughout the power supply chains. On the other hand, energy is needed for groundwater extraction and delivery (Fthenakis and Kim 2010). Irrigators around the world are facing numerous challenges, including limited water availability, insufficient water resources, and unstable energy prices (Hamdy et al. 2003; Khan et al. 2006; Zilberman et al. 2008).

It has been estimated that groundwater pumping accounts for ~ 23% of on-farm energy use for crop production in the USA, and water-related energy consumption constitutes ~ 13% of the country's total electricity consumption (Griffiths Sattenspiel and Wilson 2009; Sloggett 1982). Groundwater extraction in Iran requires the consumption of ~ 2.05 billion kWh of electricity (Karimi et al. 2012). Amount of energy required to extract one cubic meter of water varies, with the UK requiring 0.0027 kWh (Rothausen and Conway 2011), 0.50–0.61 kWh in China (Qiu et al. 2018) to as high as ~ 0.826 kWh in Iran (Karimi et al. 2012). In the North China Plains (NCP), the total energy consumption required for pumping groundwater increase from 7.72×10^9 to 10.93×10^9 kWh between 1996 and 2013. This rise can be attributed to ~ 20% increase in groundwater consumption and the lowering of the water table by ~ 0.6 m $year^{-1}$ (Qiu et al. 2018). According to Corominas (2010), in Spain, water use for irrigation has decreased by ~ 21.2% (from 8250 to 6500 m^3 ha^{-1}) between 1970 and 2007, while energy use has increased by around 657% (from 206 to 1560 kWh ha^{-1}). This increase in energy consumption has been ascribed to the lowering of the water table, which has resulted in increased energy consumption for groundwater extraction for irrigation. As a result, additional pumping costs have also increased to ~ 0.030 US$ m^{-3} for electric pumps and 0.025 US$ m^{-3} for diesel operated pumps (Qiu et al. 2018). In Iran, the unit energy cost of electric pumps was ~ 0.09 US$ kWh^{-1}, while for diesel operated pumps it was ~ 0.12 US$ kWh^{-1} (~ 1.42 US$ L^{-1}) (Qiu et al. 2018).

India has around 20 million operational groundwater wells, out of which more than 70% are operated using electricity, around 26% using diesel, and the rest rely on wind, solar, or animal power (Prayas Energy Group, 2018). Almost all of the electricity consumed in India's agriculture sector is used for groundwater extraction (Barik et al. 2017; Birner et al. 2011). During the period of 1960–2016, the electricity consumption in the agriculture sector of India increased significantly by ~ 235-times, from 0.8 to 195.5 TWh, which is much higher compared to the overall increase of ~ 77-times (from 13.8 to 1066.3 TWh) in total electricity use (ICAR, 2018). The deep tube wells, which are mostly (~ 85%) powered by electricity, require a higher amount of energy per unit water, leading to significant consequences for electricity pricing policies in the agriculture sector. Extraction of groundwater requires more energy for pumping from lower depths.

FAO (1989) classifies irrigation efficiency as good when it is around 50–60%, reasonable at 40%, and poor at 20–30%. The pumping efficiency of diesel-operated systems is determined by the combined efficiencies of transmission (60–100%), pump (40–80%), and pipes (30–95%), resulting in overall efficiency of only 0.5–27% (Fraenkel 1986). The results of various studies conducted in China and India have indicated that the pumping efficiencies typically range from 25 to 35% (Nelson et al. 2009; Shah 2009). During the initial years of operation, energy efficiency losses of pumps can be as high as 5–20% (Fleming 1989). It has been estimated that regular maintenance, repair, and optimization of pumping systems can result in significant energy savings of 5–15% (Kaur et al. 2016). According to a long-term analysis conducted between 2001 and 2017, improving overall pumping efficiency in the Rush Springs and Ogallala regions (USA) led to reductions in energy consumption of ~ 19–34% and decreases in GHGs emissions of ~ 20–52% (Handa et al. 2019). Dynamic regulation of pressure through efficient irrigation management measures can lead to energy savings of up to 20% (Díaz et al. 2009). By reducing the non-productive water consumption, there can be a decrease in water usage, resulting in a reduction in energy and resource requirements (Perry 2011). In the regions of New South Wales and South Australia, the shift from flood to pressurized irrigation systems resulted in a decrease in water application by ~ 10–66% and a reduction in energy consumption by ~ 12–44%, without any compromise on the crop yield (Jackson et al. 2010).

The utilization of pressurized micro-irrigation systems can lead to a decrease in energy consumption, especially when the pumping volumes and the total dynamic head are minimized (Hodges et al. 1994; Srivastava et al. 2003). Adopting low-pressure pipeline irrigation systems resulted in significant energy savings and reduced GHGs emissions in 11 provinces in China. It has been estimated that ~ 6.48×10^9 kWh $year^{-1}$ of energy can be saved, while GHGs emissions can be reduced by ~ 6.72 Mt $year^{-1}$ (Zhang et al. 2013a, b, c). The use of laser land leveling technology in north-western India has resulted in water savings of ~ 22–33% across different crops, and a significant reduction in water usage in the rice–wheat cropping system, amounting to ~ 1.3 million hectare-meters of water saved. This has also resulted in a considerable reduction in electricity consumption and saving ~ 766 million kWh of electricity (Aggarwal et al. 2017).

In 2013, the cost of using electric pumps for irrigation was higher compared to diesel pumps, with a cost of 0.030 US$ m^{-3} for electric pumps and 0.025 US$ m^{-3} for diesel pumps (Qiu et al. 2018). Their (Qiu et al. 2018) findings suggest that to reduce costs, it would be beneficial to replace diesel pumps with electric pumps. The unit energy cost of electric pumps in 2013 was 0.09 US$ kWh^{-1}, while for diesel pumps it was 0.12 US$ kWh^{-1} (1.42 US$ L^{-1}) (Qiu et al. 2018). A unit pumping cost varied between ~ 0.01 and 0.20 US$ depending upon different pump lifts (Llamas and Martínezsantos 2005). In Turkey, the cost of electricity for irrigation was 744.6 US$ ha^{-1} for agricultural cropland that relies solely on groundwater (Topak et al. 2009). In North China, the cost of irrigation for farmers is 55 US$ ha^{-1} including equipment cost. However, in Hebei, the cost of electricity for irrigation is higher, ranging from 125 to 150 US$ ha^{-1} (Yang et al. 2003). In USA, agriculture has been identified as the leading user of electricity and irrigation water, with a significant portion of DE being utilized for lifting groundwater, costing ~ 1.2 billion US$ annually (Rothausen and Conway 2011).

Water use and carbon footprints

Agriculture sector has been the main contributors to energy consumption and GHGs emissions (Barker et al. 2009), which emits $5.1 - 6.1 \times 10^3$ Mt CO_{2e} yr^{-1}, comprising ~ 10–12% of the total estimated GHGs emissions (Niggli et al. 2010). Groundwater pumping is a significant contributor to C emissions in countries like India, USA, China, and Pakistan, where large amounts of groundwater are extracted annually. Studies suggest that in China, the second-largest C contributor globally, groundwater pumping emits ~ 24–33 million metric tons (MMt) of CO_{2e} $year^{-1}$, which is equivalent to 6.5–9.0 MMt of C (Zou et al. 2015). Other studies (from Iran, Mexico and Pakistan) reported respective C emissions of ~ 4.95, 4.7 and 3.8 MMt of C year^{-1} from groundwater irrigation. Nelson et al. (2009) estimated that groundwater irrigation in India during 2000–01 yielded ~ 16 MMt of C year^{-1}. The estimates of groundwater irrigation in India showed a consumption of ~ 198–272 billion kWh of energy annually, releasing ~ 45.3–62.3 MMt of C in 2013–14 (Rajan et al. 2020). Electric pumps are responsible for consuming ~ 155–206 billion kWh of energy in groundwater irrigation, which makes up ~ 75% of the total energy consumption. In NCP, the C footprint associated with electricity consumption for pumping irrigation water accounted for ~ 30.3% of total emissions (Wang et al. 2015). However, Cheng et al. (2011) reported that groundwater irrigation comprised ~ 22% of the China's total C footprints associated with crop production. A study conducted in China showed that the extraction of groundwater for irrigation has been responsible for ~ 30.5–42.7% of total emissions resulting from energy activities in the agricultural sector (Zou et al. 2015). However, India has been identified as the world's third-largest GHGs emitter due to its estimated consumption of irrigation water of ~ 230 km^3 year^{-1}.

The rate of C emissions is influenced by various factors, including the height to which the water is lifted by the pump and the source of power used. The emission rates for irrigation water range from 0.15 to 0.60 kg CO_{2e} m^{-3}, with the Shaanxi province having the highest energy use rate of ~ 0.64 kWh m^{-3}, which can be attributed to the greater pump lift required (Wang et al. 2012). Carbon emissions resulting from groundwater extraction through the use of electric and diesel powered pump-sets is estimated to ~ 16–25 MMt, which accounts for ~ 4–6% of India's total emissions (Shah 2009). Based on actual pumping data of ~ 20.5 million groundwater structures, Rajan et al. (2020) reported that groundwater irrigation emits ~ 45.3–62.3 MMt of C annually, contributing ~ 8–11% of India's total C emissions. According to the analysis, the use of deep tube wells has resulted in a significant C footprint, which has become a growing environmental concern. Groundwater pumping has been found to contribute between 1.2% and 6.0% of a country's total C emissions, with Pakistan having the lowest percentage (Qureshi 2014) and the highest from India (Shah 2009). For China, Wang et al. (2012) reported that electricity associated C emissions accounts for ~ 3% of total Chinese emissions. In Iran, groundwater pumping has been responsible for ~ 3.6% of countries' total C emissions (Karimi et al. 2012). In Iran, the average energy consumption for extracting 1 m^3 of groundwater is ~ 0.826 kWh, which results in a C emission of around 0.1 kg CO_{2e} (Karimi et al. 2012).

The C intensity of electricity and diesel fuel operated pump-sets of ~ 0.4062 kg C kWh^{-1} and 0.732 kg C L^{-1}, respectively has been reported (Nelson and Robertson, 2008). The C intensity of electricity in different countries vary between 0.170 and 0.502 kg C kWh^{-1}, the largest in the USA (0.5023 kg C kWh^{-1}, Cohen et al. 2004) and the lowest for Iran (0.170 kg C kWh^{-1}, Karimi et al. 2012), while other countries viz. India and Australia in between (0.2563–0.4062 kg C kWh^{-1}, Nelson et al. 2009; CEA 2013). Using these coefficients, Shah (2009) estimated C emissions of 14.38 MMt (11.09 MMt by electricity + 3.29 MMt by diesel operated pumps) in India. In north-western India, estimates of C emissions associated to groundwater pumping for irrigation showed that over a period of 14-years (1998–2012), the use of groundwater has gone up by ~ 23%, causing a decline of ~ 5.47 m in groundwater levels. Nonetheless, there has been a surge of ~ 67% in energy requirements, leading to a staggering increase of 110% in C emissions (Kaur et al. 2016). In NCPs, the depletion of groundwater has resulted in an estimated increase of ~ 22% in energy consumption, which, in turn, has caused a rise of ~ 42% in C emissions during the period of 1996–2013 (Qui et al. 2018).

In a study conducted by Shukla et al. (2003) in Haryana and Andhra Pradesh (India), the GHGs emissions resulting from groundwater extraction were linked to the depth of extraction. The research discovered that for every meter decline in pumping water level, GHGs emissions increased by ~ 4.37% in Haryana and 6% in Andhra Pradesh. This indicates that extracting groundwater from deeper levels leads to higher GHGs emissions. Additionally, the type of crop being irrigated also impacts GHGs emissions, with rice cultivation leading to higher emissions compared to other crops. As a result, the study by Shukla et al. (2003) suggested that reducing the depth of groundwater extraction and promoting the use of more water-efficient crops could be effective strategies to reduce GHGs emissions associated with groundwater extraction. They (Shukla et al. 2003) also reported that in these regions, groundwater irrigated area increased by ~ 3% year^{-1} leads to increased GHGs emissions by ~ 6.6% year^{-1}. In Iran, groundwater extraction through pumping results in the consumption of ~ 2.05 billion kWh of electricity and ~ 2.0 MMt of fuel per year, and the process generates C emissions that make up ~ 3.6% of the country's total C emissions (Karimi et al. 2012).

Research conducted in China indicates that the use of groundwater pumping in agriculture is associated with ~ 3-times higher C emissions compared to the use of surface water pumping. This suggests that groundwater pumping has a greater impact on C emissions related to agricultural activities in China than surface water pumping (Zou et al. 2015). The adoption of improved irrigation scheduling practices leads to reduced C emissions of ~ 36% in wheat, ~ 38% in maize and ~ 47% in sugar beet (Karimi et al. 2012). The C emissions associated with groundwater irrigation varied across different crops, with sugarcane having the highest emissions (~ 93 kg CO_{2e} ha^{-1} m^{-1}), followed by rice (~40 kg CO_{2e} ha^{-1} m^{-1}), wheat (~28 kg CO_{2e} ha^{-1} m^{-1}), mustard (~26 kg CO_{2e} ha^{-1} m^{-1}), pigeon pea (~14 kg CO_{2e} ha^{-1} m^{-1}), and pearl millet having the lowest emissions (~4 kg CO_{2e} ha^{-1} m^{-1}). This indicates that the choice of crop has a significant impact on the amount of C emissions resulting from groundwater irrigation (Patle et al. 2016).

Based on calculations, considering the efficiency of electric pumps and an estimated emission factor for CO_{2e}, pumping of 1000 cubic meters of groundwater per meter using an electric pump results in the release of ~4.22–13.5 kg CO_{2e}. The efficiency of electric pumps is estimated to be around 30–40%, which contributes to the range in the estimate of C emissions. Additionally, the emission factor for CO_{2e} kWh^{-1} is estimated to be between 0.62 and 1.49 kg CO_{2e} kWh^{-1}, which also contributes to the range in the estimate of C emissions (Mishra et al. 2018). The most effective strategy for reducing C emissions associated with groundwater pumping has been to improve the pumping efficiency. Studies have shown that by increasing the pump efficiency from 35 to 51%, C emissions can be reduced by ~32%. This indicates that improvements in the design and technology of pumps can have a significant impact on reducing C emissions related to groundwater pumping (Patle et al. 2016; Pradeleix et al. 2015; Wang et al. 2012). In north-western India, Kaur et al. (2016) reported that C emissions were reduced by ~26% with improved pump efficiency of ~10% coupled with a saving of ~1340 M kWh of energy. In groundwater irrigated regions of USA, Jackson et al. (2010) reported C emissions savings of ~12–44% with the adoption of efficient water management technologies. In China, irrigation through low pressure pipeline system has shown potential saving in energy (6.48×10^9 kWh $year^{-1}$) with substantial mitigation of C emissions (~6.72 Mt $year^{-1}$) (Zhang et al. 2013a, b, c). Zou et al. (2015) reported that low pressure pipes reduce C emissions by ~177 kg CO_{2e} ha^{-1}. A long-term study (2001–2017) showed that improving overall pumping efficiency in the Rush Springs and Ogallala regions of USA resulted in energy consumption reductions of ~19–34%. Furthermore, it was observed that these reductions in energy consumption led to decreases in GHGs emissions by ~20–52%, which indicates a strong correlation between improvements in pumping efficiency, reductions in energy consumption and decreased GHGs emissions (Handa et al. 2019). Recent estimates suggest that in north-western India, replacing only ~10% of the total area under rice cultivation with direct seeded basmati could have multiple benefits. Specifically, this change could result in a reduction of ~1.14 million kilowatt-hours of electricity required, along with a decrease in C emissions of ~0.17 megatons. In the USA, the drip irrigation system produced ~45% lower C emissions, with a total of ~216 kg CO_{2e}, when compared to the furrow irrigation system, which emits ~395 kg CO_{2e} (Lal 2004). Adopting solar-based pumps with a capacity of 2 horsepower for extracting groundwater and coupling them with drip irrigation systems could lead to the conservation of ~6000 units of electricity per year with an average operational period of 8 h. Such system exerts a significant improvement over conventional flood irrigation techniques in terms of energy efficiency and C neutrality in agriculture (Bassi 2018). Nonetheless, the improvement in pumping efficiency leads to cost saving of ~17% in south-eastern Spain (Mora et al. 2013) and ~33% for irrigated areas in central Tunisia (Luc et al. 2006). In Iran, Wang et al. (2012) reported that C emissions would be doubled with ~20% decrease in electric pump efficiency; whilst ~20% increase in pump efficiency would leads to reduced C emissions by ~1/3rd. A study conducted in Iran revealed that enhancing irrigation efficiency by ~65% results in a reduction of ~20% in irrigation water demand. As a consequence, C emissions get reduced by ~16% in wheat, 19% in maize, and 30% in sugar beet crops (Karimi et al. 2012).

Nutrient management, energy and carbon footprints nexus

On a global scale, it is observed that ~50% of the applied fertilizer-N is taken up by crops as above-ground biomass, while the remaining half either gets lost from fields or stays in the soil, which leads to pollution of air and water, causing severe environmental consequences.

(Davidson et al. 2016). Efficient nutrient management has a significant impact on energy usage and C footprints in crop production due to significant changes in nutrient use efficiency (NUE) (Davidson et al. 2016; Singh et al. 2021a, b, c). Chemical fertilizers are manufactured from finite resources, which are highly energy intensive processes (i.e., Haber–Bosch process) (Skowronska, and Filipek 2014). The practice of applying chemical fertilizers to provide nutrients that are bio-available often has undisclosed costs in terms of energy consumption and C emissions (Lal 2004; Singh and Benbi 2020a). Mismanagement of chemical fertilizers in agriculture, facilitated by their high subsidies, leads to reduced fertilizer use efficiency and subsequent nutrient losses in aquatic ecosystems. Such practices often results in incurring hidden costs in terms of energy and C (Tilman 1999; Good and Beatty 2011), and thereby interrupts the nutrient cycles and cause eutrophication (Vitousek et al. 1997; Carpenter et al. 1998; Bennett et al. 2001). The N footprint per capita in the USA is 39 kg N $year^{-1}$, with 60% of this footprint being attributed to food production. On the other hand, in Tanzania, the per capita N footprint is only ~15 kg N $year^{-1}$, with ~80% of it being associated with food production (Galloway et al. 2014).

Similarly, element phosphorus (P) is closely connected to a complex and interdependent nexus of water, energy, and food security that is becoming more vulnerable over time (Jarvie et al. 2015). China's N and P footprints have shown a significant increase from 1976 to 2013, with per capita N increasing from 5.4 to 19.3 kg N year^{-1}, and P increasing from 1.20 to 4.77 kg P year^{-1}. These elevated footprints are linked to an increase in the consumption of meat and vegetables in China (Oita et al. 2020). These footprints in India gradually increased since 1976 due to an increase in milk and vegetable consumption, with a range of 8.5–11.4 kg N capita^{-1} year^{-1} and 0.99–1.6 kg P capita^{-1} year^{-1} in 1976–2013. Meanwhile, in Japan, the footprints increased until 1993 with a range of 12.2–28.3 kg N capita^{-1} year^{-1} and 2.59–8.43 kg P capita^{-1} year^{-1} in 1961–1993, before declining to 21.8 kg N capita^{-1} year^{-1} and 6.05 kg P capita^{-1} year^{-1} in 2013. The increase was mainly due to a constant rise in meat consumption, a decrease in cereals, and improvements in NUE (Oita et al. 2020).

The third major nutrient, potassium (K) is a crucial mineral nutrient that plays a pivotal role in the growth and development of crops (Bhattacharyya et al. 2018). It is essential for various physiological processes, including root and leaf growth, stomatal regulation, photosynthesis, phloem loading of sucrose, grain formation, disease resistance, xylem water transport, and tolerance to abiotic stresses (Zhang et al. 2022; Yang et al. 2023). During water deficit conditions, K enhances root water uptake by elevating intracellular osmotic pressure and promoting aquaporin activity (Coffey et al. 2018; Yang et al. 2023). Additionally, it influences the conductance of CO_2 and water by modulating stomatal conductance and mesophyll structure (Liu et al. 2021; Yang et al. 2023). The impact of K fertilization on crop water use efficiency hinges on the balance between carbon fixation benefits and the water dissipation costs it entails. This dynamic is not only influenced by K fertilization levels but also by factors such as the local climate, soil properties, and agronomic practices—elements often overlooked in studies due to their difficulty in quantitative assessment.

Energy input in cereals, pulses and oilseed crops production

Agricultural production relies heavily on energy inputs, and the growing use of NRE sources has become a crucial issue for both developed and developing countries (AghaAlikhani et al. 2013). The agriculture sector primarily relies on eight main sources of energy inputs, including seed, human labor, diesel fuel, chemical fertilizers, biocides (such as herbicides, insecticides, and fungicides), agricultural machinery, irrigation, and electricity (Khan et al. 2009; Pishgar-Komleh et al. 2012; Nabavi-Pelesaraei et al. 2016; Singh et al. 2020) (Table 1). In rice production under both traditional and mechanized systems, diesel fuel consumption exhibited highest share, followed by chemical fertilizers. The E_I consumption in rice production was estimated to be 71,092 MJ ha^{-1} under traditional systems and 79,460 MJ ha^{-1} under mechanized systems. Seed energy had the smallest energy input, accounting for ~ 2.4% of the E_I in rice cultivation (Kazemi et al. 2015) In rice cultivation, chemical fertilizers accounted for ~ 16% of E_I, followed by diesel fuel which accounted for ~ 37.8%, and agri-machinery accounting for ~ 25.6%. Meanwhile, irrigation water accounted for ~ 12% of E_I in rice cultivation (Kazemi et al. 2015). Singh et al. (2019a) found that in south-western Punjab (India), irrigation water was the largest contributor towards E_I in rice cultivation, while seed energy was the smallest (Table 1). In Gulian Province of Iran, Pishgar-Komleh et al. (2012) reported that of E_I of 39,333 MJ ha^{-1} in rice cultivation, diesel fuel energy had the largest share (46%), followed by chemical fertilizer (36%), seed (8%), and biocide (6%). In wheat cultivation, the chemical fertilizers had the largest proportion of E_I, accounting for 45.7% of E_I of 15,579 MJ ha^{-1}. On the other hand, human labor had the smallest energy share, accounting for only 0.9% of the E_I (Soltani et al. 2013).

In wheat cultivation, the agri-machinery energy input contributed ~ 9.3% of the E_I. Chemical fertilizers had the largest share (~ 45.7%) of E_I with fertilizer-N contributing ~ 38.3%, and fertilizer-P and fertilizer-K contributing approximately 4.7% and 2.7%, respectively. According to Khoshnevisan et al. (2013a), the most significant factors contributing towards E_I in wheat production were electricity, chemical fertilizers and irrigation water. The consumption of electricity energy is predominantly associated with the use of electric pumps for extracting underground water to meet irrigation requirements (Khoshnevisan et al. 2013a; Singh et al. 2019a, b).

Singh et al. (2019b) conducted a study on wheat cultivation in north-western India and found that fertilizers had the highest contribution, accounting for 44% of E_I. This was followed by irrigation at 15%, with electricity and diesel fuel having similar contributions at 14.7%. Table 1 showed that of the energy input related to fertilizers, which accounted for ~ 44% of E_I, fertilizer-N constituted ~ 40.8%. Meanwhile, the remaining proportion was shared by fertilizer-P and fertilizer-K. They (Singh et al. 2019b) reported that E_I in wheat cultivation under rice–wheat (25,452 MJ ha^{-1}) and cotton-wheat (25,579 MJ ha^{-1}) cropping systems did not differ significantly. Taghavifar and Mardani (2015) conducted a study on wheat production in West Azerbaijan and found that the major energy inputs were diesel fuel and chemical fertilizers. The E_I was approximately 30,626 MJ ha^{-1}, and the relative contribution of various energy sources was ranked in the following order: human labor

Table 1 Component-wise energy input in field crops grown in different agro-climatic regions

Crop	Country (region)/climate	Energy input (MJ ha^{-1})								References
		Seed	Human	Diesel fuel	Chemical fertilizers	Biocides	Machinery	Irrigation	Electricity	
Rice	Iran (Golestan, Gulian and Mazandaran Provinces) Mean annual precipitation = 450–1041 mm, Relative humidity = 68–78%	1469	489	22,789	9731	990	15,469	7276	2310	Kazemi et al. (2015)
Rice	Iran (Gulian Province) Average annual rainfall = 1100 mm, mean maximum temperature = 33 °C, mean minimum temperature = 0 °C	3097	1315	4255	14,066	2387	396	–	2287	Pishgar-Komleh et al. (2011)
Rice	India (Mansa district, south-western Punjab) Mean annual temperature = 24–27 °C, mean annual rainfall = 300–450 mm, hot, *typic* arid	170	263	4587	12,935	3740	419	20,971	9250	Singh et al. (2019a)
Rice	India (West Bengal)	1153	2291	2694	2875	–	361	–	–	Chauhan et al. (2006)
Wheat	Iran (Gorgan Province) Temperate, Sub-humid, mean annual rainfall = 607 mm, mean annual temperature = 17.8 °C, Solar radiation = 15.7 MJ m^{-2} d^{-1}	2721	215	3560	7123	316	1452	–	309	Soltani et al. (2013)
Wheat	Bangladesh (Dinajpur and Rajshahi region)	2375	1644	–	6287	49	–	1914	–	Rahman and Hasan (2014)
Wheat	Azerbaijan (West)	2387	186	3458	9074	538	2147	–	853	Taghavifar and Mardani (2015)
Wheat	Iran (Khuzestan Province)	2428	231	9296	13,632	2126	1129	9316	–	Nabavi-Pelesaraei et al. (2016)
Wheat	India (Mansa district, south-western Punjab) Average annual rainfall = 378 mm, semi-arid, sub-tropical	1756	130	3643	11,531	240	678	3835	3753	Singh et al. (2019b)
Wheat	Happy seeder technology for rice residue management India (Mansa district, south-western Punjab) Average annual rainfall = 378 mm, semi-arid, sub-tropical, hot *typic* arid	2109	109	2104	11,366	145	364	3089	4203	Singh et al. (2021b)
Wheat	Super seeder technology for rice residue management India (Mansa district, south-western Punjab, north-western India)	2105	92	2168	10,098	134	329	3930	3400	Singh et al. (2023)
Wheat	*Efficient decision making units (DMUs)* India (Mansa district, south-western Punjab) Average annual rainfall = 300–450 mm, semi-arid, sub-tropical	1744	118	3350	11,091	154	1354	3770	3468	Singh et al. (2021d)
	Inefficient DMUs	1757	138	3908	11,562	288	1411	3778	4068	
Wheat	India (Bathinda and Mansa districts of Punjab), average annual rainfall of ~ 408 mm in Bathinda and 300–450 mm in Mansa districts	1778	114	3776	12,123	476	621	3194	2630	Kaur et al. (2024)

Table 1 (continued)

Crop	Country (region)/climate	Energy input (MJ ha^{-1})								References
		Seed	Human	Diesel fuel	Chemical fertilizers	Biocides	Machinery	Irrigation	Electricity	
Wheat	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	4710	19	3242	10,115	120	475	–	–	Canakci et al. (2005)
Wheat	Iran (Isfahan Province)	4041	159	175	23,269	175	1896	6171	39,567	Khoshnevisan et al. (2013a)
Wheat	India (Himachal Pradesh) Low altitude region	–	1727	913	6480	–	352	2912	–	Mani et al. (2007)
Barley	Iran (Hameden Province)	3201	163	5864	6935	183	1142	4768	2770	Mobtaker et al. (2010)
Maize	Iran (Kermanshah Province) Average annual rainfall = 450 mm, average annual temperature = 14.2 °C, monthly maximum temperature = 27.6 °C, monthly minimum temperature = 2.2 °C	368	526	10,248	19,837	260	1091	5462	12,694	Yousefi et al. (2014)
Maize	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	393	240	9897	13,473	336	1246	–	–	Canakci et al. (2005)
Maize	India (Himachal Pradesh) Low altitude region	569	2142	1034	4020	–	470	52	–	Mani et al. (2007)
Maize	China (Wendeng, Wendeng County)	3201	516	3071	27,677	806	1361	–	–	Ren et al. (2012)
Cotton	Turkey (Adiyaman Province)	254	1128	2948	5351	-	3814	4253	–	Baran (2016)
Cotton	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	1560	1138	11,818	17,697	1260	1419	–	–	Canakci et al. (2005)
Cotton	Iran (Golestan), sub-humid, Mean annual temperature = 17.6 °C, Solar radiation = 15.7 MJ m^{-2} d^{-1}	938	2783	6185	15,392	1887	1856	6160	1120	Sami and Reyhani (2018)
Cotton	Iran (Isfahan Province)	1941	1684	24,863	10,401	1175	1565	6518	2801	Zahedi et al. (2014)
Cotton	Turkey (Hatay Province)	818	1050	3334	8861	813	308	7375	–	Erdal et al. (2009)
Cotton	China (Jieshishan, Wudi County)	1141	3191	2325	32,793	4261	5266	305	–	Ren et al. (2012)
Oilseed (Canola)	Iran (Mazandaran Province)	33	143	5217	8012	385	1121	–	–	Mausai-Avval et al. (2017)
Groundnut	Iran (Kiashahr Province)	2468	1417	8774	5870	423	555	–	658	Firouzi and Aminpanah (2012)
Sesame	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	260	699	4196	3903	156	512	–	–	Canakci et al. (2005)
Soybean	Iran (Golestan Province) Average annual rainfall = 442 mm, Average annual temperature = 18 °C	250	380	4950	7020	900	960	3370	15,940	Mohammadi et al. (2013)
Soybean	Iran (Golestan Province)	248	381	4953	8619	902	963	3369	15,938	Mousavi-Avval et al. (2011)
Soybean	Iran (Kordkuy county), Golestan province	922	450	11,298	2581	234	1026	1115	401	Ramedani et al. (2011)
Sweet sorghum	China (Jieshishan, Wudi County)	1038	581	4803	15,801	773	3569	524	–	Ren et al. (2012)
Sweet sorghum	China (Wendeng, Wendeng County)	1811	1259	1230	20,645	2277	1521	–	–	Ren et al. (2012)

(0.6%) < biocides (2%) < electricity (3%) < agri-machinery (7%) < seed (8%) < chemical fertilizers (30%) < diesel fuel (50%). Nabavi-Pelesaraei et al. (2016) reported that of the E_I of 39,890 MJ ha^{-1} in wheat cultivation in Iran (Khuzestan Province), diesel fuel (9296 MJ ha^{-1}; ~ 23%) and chemical fertilizers (13,632 MJ ha^{-1}; ~ 34%) were the two major energy inputs (Table 1).

However, in the Isfahan Province of Iran, Khoshnevisan et al. (2013a) reported much higher E_I (80,173 MJ ha^{-1}) with electricity (39,567 MJ ha^{-1}; ~ 49%) and chemical fertilizers (23,269 MJ ha^{-1}; ~ 29%) as major contributors towards E_I in wheat production. Fertilize-N alone comprised ~ 24% of total chemical fertilizer related energy input in wheat production, while remaining ~ 5% was shared by fertilizer-P and K (Khoshnevisan et al. 2013a). The study conducted by Mobtaker et al. (2010) on barley production in Hamedan Province of Iran reported that the major energy inputs were diesel fuel (23.4% of E_I of 25,027 MJ ha^{-1}) and chemical fertilizers (27.7%), contributing approximately 51% towards the E_I. Irrigation water was identified as the third-largest energy input, accounting for 19.1% of E_I, followed by seed at 12.8% and electricity at 11.1% (Fig. 2a). Similarly, Ziaei et al. (2015) reported that in barley production the largest share of energy (32.29%) was allocated to chemical fertilizers, followed by diesel fuel (29.45%) and irrigation water (15.27%). Seed and agricultural machinery contribute 13.48% and 8.37%, respectively, while human labor accounts for a minimal 1.11%. Interestingly, biocides do not contribute to the E_I, highlighting a focus on other resources for crop production (Fig. 2b).

In maize ecosystem, Yousefi et al. (2014) reported that E_I of 50,485 MJ ha^{-1} had the highest contribution from the application of chemical fertilizers (39.3% of E_I) followed by electricity (25.1%) and diesel fuel (20.3%) and irrigation water (10.8%) (Table 1, Fig. 3a). In Nepal, Poudel et al. (2019) reported the largest share (50.07%) in maize production comes from farmyard manure (FYM), highlighting its significant role in the farming system. Chemical fertilizers contribute 19.63%, followed by diesel fuel at 17.04%. Seed and human labor account for 4.57% and 4.99%, respectively, while agricultural machinery contributes 3.54%. Biocides make a minimal contribution (0.16%), and there is no energy input from irrigation water or electricity in this system (Fig. 3b). Similarly, in Nigeria Kosemani and Bamgboye (2021) reported largest share of chemical fertilizers in maize production (45.4% of E_I), followed by diesel fuel (35.9%), which highlights their dominant role in the farming system. Agricultural machinery contributes ~ 10.7%, while herbicides and seed inputs account for ~ 3.88% and 3.61%, respectively (Fig. 3c).

Maize cultivation in the low altitude (350–600 m) hilly region of Himachal Pradesh (India) had a E_I of 10,487 MJ ha^{-1}, of which chemical fertilizers (48.5% of E_I) had the highest, while irrigation had the lowest contribution (0.62% of E_I) (Mani et al. 2007). According to the study, maize production at middle altitude regions (651–1800 m) and high altitude regions (> 2201 m) required 38.5% and 57.9% lower E_I, respectively, compared to production at low altitude hilly regions. Ren et al. (2012) reported that maize production in Wendeng County in China had E_I of 32,632 MJ ha^{-1} with ~ 76% contribution of chemical fertilizers alone. Relative contribution of various inputs to the E_I associated with maize production was lowest for human labor at 1.4%, followed by biocides (2.2%), agri-machinery (3.7%), diesel fuel (8.4%) and seed (8.7%) (Table 1). Similar energy input patterns were observed for sweet sorghum production, with chemical fertilizers having the highest share (~ 72%) and diesel fuel has the lowest share (4.3%). Human labor, agri-machinery, and biocides were the other energy inputs in sweet sorghum production in China, with contributions of 4.4%, 5.3%, and 7.9% of E_I, respectively (Ren et al. 2012).

In cotton ecosystem, E_I of 17,747 MJ ha^{-1} comprised highest contribution of chemical fertilizers accounting for ~ 30.2% of E_I, followed by irrigation water (24%), agri-machinery (21%), diesel fuel (16.7%) and seed (1.4%) (Baran 2016). In Antalya Province (Turkey), Canakci et al. (2005) reported energy input of 156, 1138, 118, 17,697, 12,060 and 1419 MJ ha^{-1} for seed, human labor, diesel fuel, chemical fertilizers, biocides and agri-machinery, respectively (Table 1). In Golestan Province of Iran, Sami and Reyhani (2018) reported that ~ 44% of E_I was attributed to the application of chemical fertilizers in cotton cultivation. The energy contribution of diesel fuel and irrigation water towards the E_I in cotton farming was ~ 18% each. Meanwhile, the energy consumption associated with seed and biocides accounted for ~ 5.4% of E_I (Table 1). Zahedi et al. (2014) reported E_I of 52,508 MJ ha^{-1} in cotton cultivation in Iran (Isfahan Province) had the highest contribution from diesel fuel (24,863 MJ ha^{-1}; ~ 47.4% of E_I), followed by chemical fertilizers (10,401 MJ ha^{-1}; ~ 19.8% of E_I) and irrigation water (6518 MJ ha^{-1}; ~ 12.4% of E_I) in Isfahan Province of Iran. In Hatay Province (Turkey), Erdal et al. (2009) revealed that chemical fertilizers were the major energy input (~ 45% of 19,558 MJ E_I ha^{-1}), followed by irrigation water (~ 22%; 4375 MJ E_I ha^{-1}) and the diesel fuel (~ 17%; 3334 MJ ha^{-1}) in cotton cultivation. In Jieshishan (Wudi County) region in China, Ren et al. (2012) concluded that seed energy was the smallest (1141 MJ ha^{-1}; ~ 2.2% of E_I) and the chemical fertilizer energy was the largest (32,793 MJ ha^{-1}; ~ 63% of E_I) energy input in cotton production (Table 1).

In canola (oilseed) cultivation, Mausai-Avval et al. (2017) reported that seed energy was the smallest energy input, while the chemical fertilizer had the largest energy share towards E_I. A study on groundnut cultivation in Kiashahr Province, Iran revealed that the E_I was 20,164 MJ. The

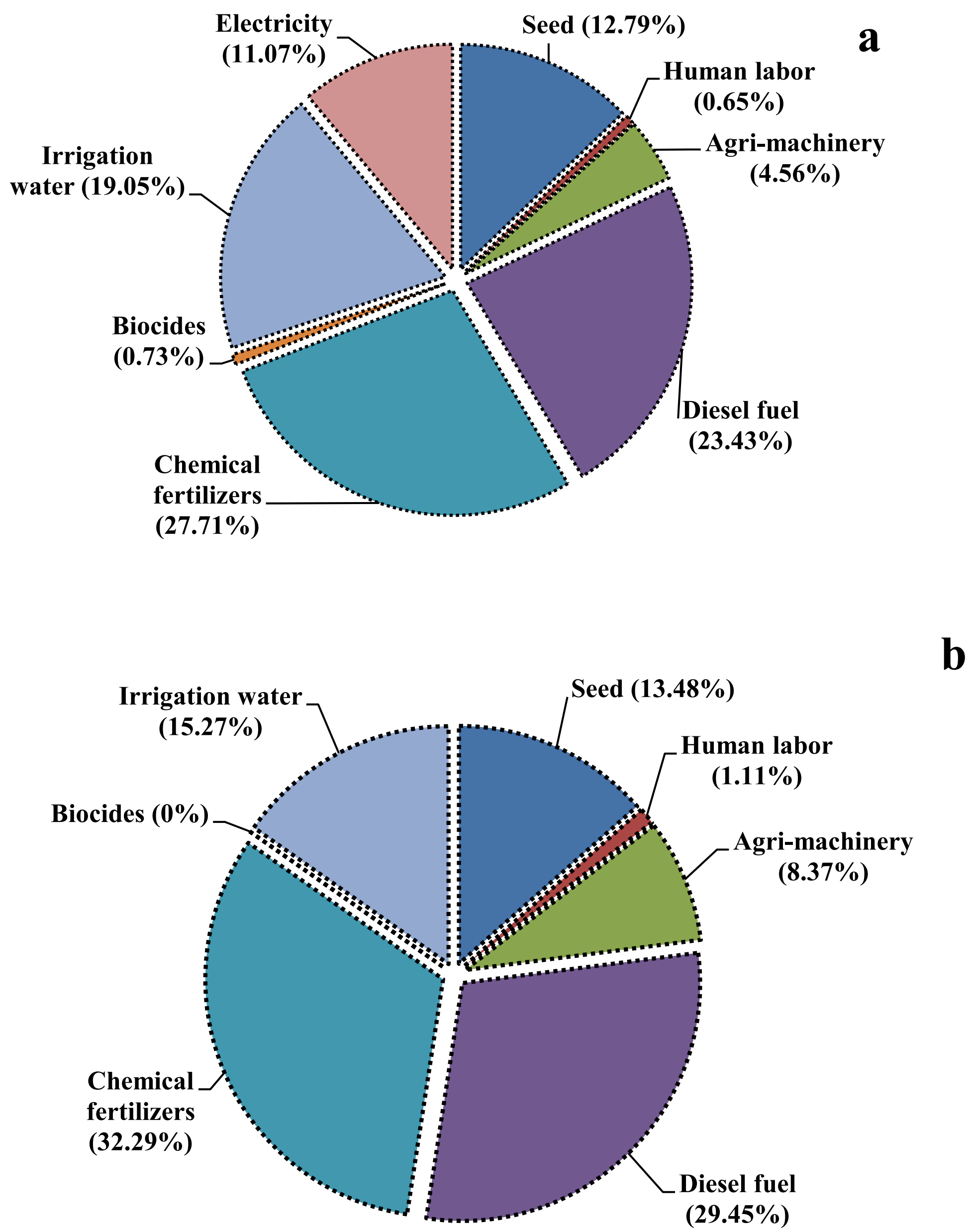

Fig. 2 Contribution of different energy inputs towards total energy use in barley production. (Source: **a** Mobtaker et al. 2010, **b** Ziaei et al. 2015)

largest contributor to the E_I was diesel fuel, accounting for ~ 43.5% (8774 MJ ha^{-1}), followed by chemical fertilizers (~ 29%; 5870 MJ ha^{-1}), seed (~ 12.2%; 2468 MJ ha^{-1}), electricity (~ 3.3%; 658 MJ ha^{-1}) and human labor (~ 7%; 1417 MJ ha^{-1}) (Table 1) (Firouzi and Aminpanah 2012). Mohammadi et al. (2013) reported that in Golestan Province (Iran) soybean cultivation incur a E_I of 35,370 MJ ha^{-1}, with highest contribution from electricity (~ 45.1% of E_I) and chemical fertilizers (~ 19.8% of E_I). A study on energy input budgeting in soybean cultivation in Golestan Province, Iran, reported that the relative contribution of various energy inputs towards E_I was ranked as follows: seed (0.7%) < human labor (1.1%) < biocides (2.5%) < agri-machinery (2.7%) < irrigation water (9.5%) < diesel fuel (14%) < chemical fertilizer (24.4%) < electricity (45.1%). This indicates that electricity was the most significant energy input, accounting for ~ 45.1% of E_I, followed by chemical fertilizer (24.4%) and diesel fuel (14%) (Mousavi-Avval et al. 2011). Ramedani et al. (2011) conducted a study on the energy inputs in soybean production in Golestan Province, Iran, and reported different inputs contributed to E_I in the following order: biocides (1% E_I) < electricity ≈human labor (2%) < seed (5%) < agri-machinery ≈ irrigation water (6%) < chemical fertilizers (14%) < diesel fuel (64%) (Table 1).

Ren et al. (2012) conducted a study to compare E_I in sweet sorghum cultivation in two regions (Wendeng and Wudi) in China, and reported that chemical fertilizers had largest

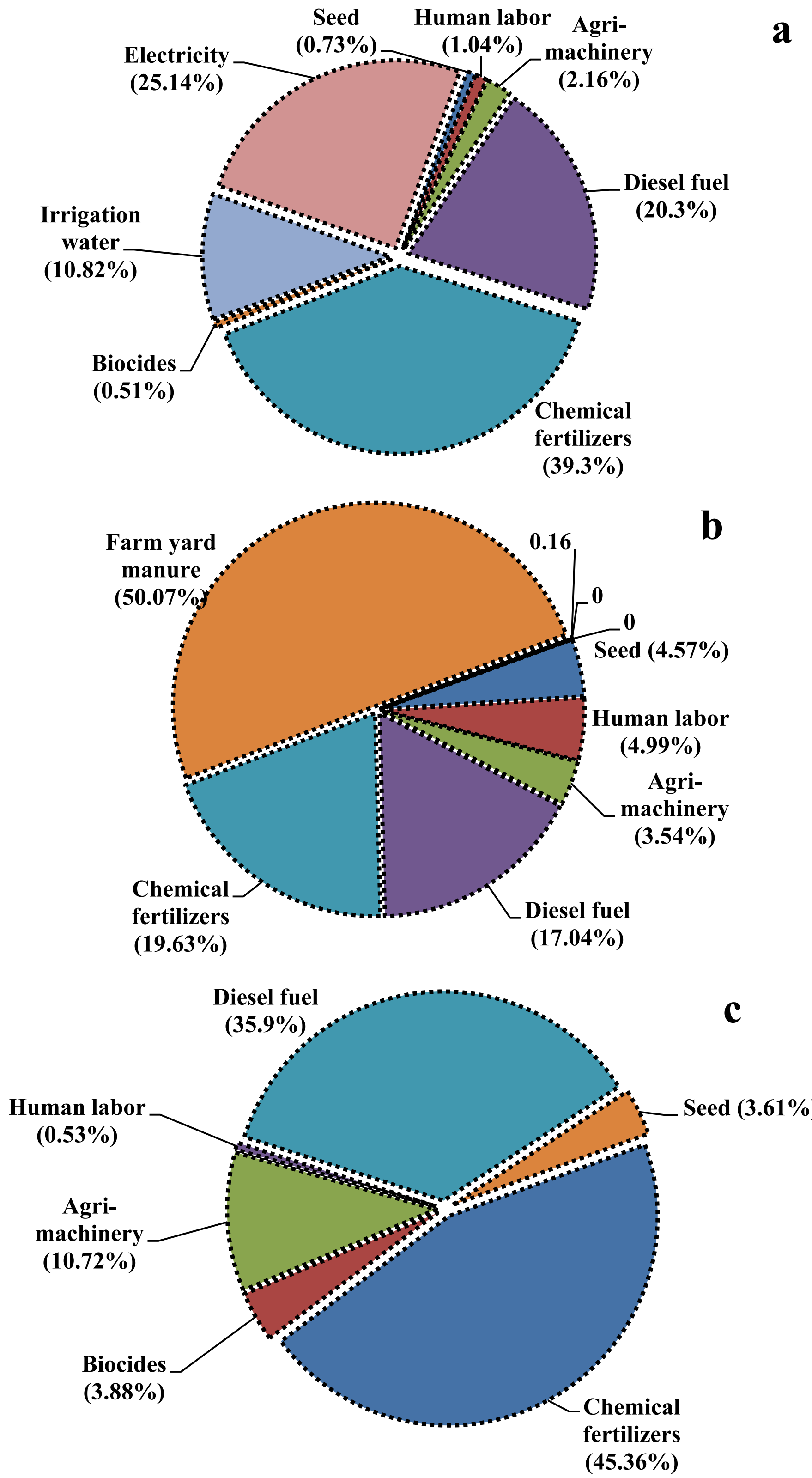

Fig. 3 Contribution of different energy inputs towards total energy use in maize production. (Source: **a** Yousefi et al. 2014, **b** Poudel et al. 2019, **c** Kosemani and Bamgboye 2021)

energy input, accounting for 58–72% of E_I. Interestingly, the study found that the contribution of diesel fuel energy towards E_I was higher in Wudi region, accounting for ~ 17% of E_I of 27,089 MJ ha^{-1}, compared to the Wendeng region, where it only accounted for ~ 4.3% of E_I of 28,743 MJ ha^{-1}. These findings suggest that reducing the use of chemical fertilizers and diesel fuel in sweet sorghum cultivation could significantly reduce the overall energy input and improve the sustainability of the process. It may be worthwhile to explore alternative inputs that could help reduce the reliance on these energy-intensive inputs in both regions. On the other hand, in the case of sweet sorghum cultivation, the energy input from biocides was found to be higher in the Wendeng region, accounting for ~ 7.9% of E_I (2277 MJ ha^{-1}), compared to the Wudi region, where biocide energy input accounted for ~ 2.9% of E_I (773 MJ ha^{-1}). Additionally, agri-machinery energy input was found to be ~ 57% lower in sweet sorghum cultivation in the Wendeng region compared to the Wudi region (Table 1).

Energy input in greenhouse and open field vegetable cultivation

In a study conducted by Khoshnevisan et al. (2013a) on the E_I budget of greenhouse cucumber cultivation in Esfahan Province, Iran, it was found that electricity was the major energy input, accounting for ~ 26.5% of E_I of 442,904 MJ ha^{-1} (Table 2). On the other hand, the contribution of chemical fertilizers towards E_I was only ~ 3.7% (1,667,165 MJ ha^{-1}). Their (Khoshnevisan et al. 2013a) study also revealed that natural gas was responsible for ~ 65.7% of the E_I for greenhouse cucumber production, which was used for heaters, ventilation, and drip irrigation systems. Kuswardhani et al. (2013) conducted a study on E_I in tomato cultivation in West Java, Indonesia, and reported that human labor, chemical fertilizers, biocides, diesel fuel, and agri-machinery were the major energy inputs, accounting for ~ 25.5, 26.3, 15.6, 9.5 and 1.6% of E_I, respectively. The E_I in greenhouse cultivation of tomato, chili (medium and high land), and lettuce were 47,619, 41,552, 58,843, and 24,537 MJ ha^{-1}, respectively. In contrast, E_I for open field cultivation of tomato, chili (medium and high land), and lettuce were 49,009, 41,040, 57,944, and 23,866 MJ ha^{-1}, respectively.

This study (Kuswardhani et al. 2013) also revealed that E_I in greenhouse production of tomato and chili was higher than in open field production, mainly due to the higher use of fertilizers, followed by human interventions for management, chemicals, and manure. Interestingly, the study found that the highest electricity consumption (10,737 MJ ha^{-1}; ~ 43% of E_I) was due to the high power consumption for the drip irrigation system used in greenhouse lettuce production. On the other hand, Mohammadi-Barsari et al. (2016) investigated the energy inputs in watermelon production in Kiashahr Province, Iran, and found that E_I was 16,595 MJ ha^{-1}, with chemical fertilizers accounting for the highest proportion (~ 75.2% of E_I), followed by diesel fuel (12.9%), agri-machinery (9.3%), and human labor (1.4%). These findings suggest that reducing the use of energy-intensive inputs such as chemical fertilizers and diesel fuel could potentially enhance the sustainability of watermelon production in Kiashahr Province, Iran.

The E_I for strawberry production under open field and greenhouses was 35,092 and 1,356,933 MJ ha^{-1}, respectively (Khoshnevisan et al. 2014a) (Table 2). Fertilizer-N accounted for ~ 41% of E_I in open field strawberry production, followed by human labor (16%) and biocides (9%). Strawberry production in open fields relied heavily on manual labor and had low machinery energy input. On the other hand, greenhouse production systems required high natural gas energy input (~ 58.4% of E_I) and electricity (27.4% of E_I) for heating and drip irrigation systems powered by electrical pumps. According to a study on eggplant cultivation in Iran, the total energy input was found to be 13,911 MJ ha^{-1}. In eggplant production, diesel fuel emerged as largest energy input accounting for ~ 49.2% of E_I. Chemical fertilizers, including N (30.3%), P (2.7%) and K (1.4%) were the second-largest energy input (Nabavi-Pelesaraei et al. 2013). According to Erdal et al. (2007), E_I in sugar beet production was 39,686 MJ ha^{-1}, with chemical fertilizer energy accounting for ~ 49.3% and diesel fuel energy ~ 24.2% of E_I. A comparison between potato farmers who owned machinery (group-I) and those who did not (group-II) showed that group-I required 534.9 h ha^{-1} of human labor and 47.2 h ha^{-1} of machine power, while group-II required 532.7 h ha^{-1} of human labor and 50.8 h ha^{-1} of machine power (Zanganeh et al. 2010). The E_I for potato production in group-I and group-II were reported as 153,071 and 157,151 MJ ha^{-1}, respectively, and the major energy input in group-I was attributed to electricity (~ 36.6%) and chemical fertilizers (~ 24.8%), while for group-II, the use of chemical fertilizers (~ 36.9%) was the most energy-intensive input, followed by electricity and diesel fuel.

Energy input in fruit production

According to Nabavi-Pelesaraei et al. (2013), orange production in Gulian Province, Iran, consumed E_I of 25,582 MJ ha^{-1} (Table 3). Among the various inputs, chemical fertilizers were major energy input accounting for ~ 47.7% of E_I, while biocides (599 MJ ha^{-1}; ~ 2.3%) and human labor (851 MJ ha^{-1}; ~ 3.3%) were least energy-intensive inputs. In Sari region of Iran, Qasemi-Kordkheili and Nabavi-Pelesaraei (2014) reported that in nectarine production, the major energy inputs were human labor (2624 MJ ha^{-1}; ~ 6.8%), agri-machinery (3855 MJ ha^{-1}; ~ 10.1%), diesel fuel (7929 MJ ha^{-1}; ~ 20.6%), chemical fertilizers

Table 2 Component-wise energy input in vegetable crops grown in different agro-climatic regions

Crop	Country (region)/climate	Energy input (MJ ha^{-1})								References
		Seed	Human	Diesel fuel	Chemical fertilizers	Biocides	Machinery	Irrigation	Electricity	
Greenhouse cultivation										
Cucumber	Iran (Esfahan Province)	1.1	14,094	8917	45,230	5346	1127	24,202	442,904	Khoshnevisan et al. (2013a)
Tomato	Indonesia (West Java, Banding and Sukabumi provinces)	–	12,142	4505	12,544	7424	754	416	835	Kuswardhani et al. (2013)
Tomato	India (Bathinda district) Mean minimum temperature = 3.9^{O}C, mean maximum temperature = 42^{O}C	0.026	4573	3519	3830	4486	38.7	3898	24,330	Sarvpriya-Singh et al. (2025)
Chilly	Indonesia (West Java, Banding and Sukabumi provinces) (*Medium land*)	–	13,240	–	13,816	9020	904	499	1074	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java, Banding and Sukabumi provinces) (*High land*)	–	15,122	–	18,816	12,690	1114	669	1432	Kuswardhani et al. (2013)
Lettuce	Indonesia (West Java, Banding and Sukabumi provinces)	–	2269	394	5018	–	71	48	10,737	Kuswardhani et al. (2013)
Strawberry	Iran (Gilan Province)	–	25,134	12,785	81,560	12,785	1155	24,353	372,068	Khoshnevisan et al. (2014a)
Open field cultivation										
Watermelon	Iran (Kiashahr Province) Average annual rainfall = 1496 mm	0.42	232	2142	11,843	202	1543	–	–	Mohammadi-Barsari et al. (2016)
Tomato	Indonesia (West Java, Banding and Sukabumi provinces)	–	10,451	4505	12,961	11,114	729	250	–	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java, Banding and Sukabumi provinces) (*Medium land*)	–	11,632	0	12,917	11,520	869	208	895	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java, Banding and Sukabumi provinces) (*High land*)	–	13,514	0	18,117	14,584	1122	354	1253	Kuswardhani et al. (2013)
Lettuce	Indonesia (West Java, Banding and Sukabumi provinces)	–	3428	375	5018	7960	71	48	1342	Kuswardhani et al. (2013)
Tomato	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	5590	2087	13,651	21,441	852	1977	–	–	Canakci et al. (2005)
Melon	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	2018	984	11,218	17,614	696	1598	–	–	Canakci et al. (2005)
Watermelon	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	1501	891	11,701	17,614	612	1659	–	–	Canakci et al. (2005)
Strawberry	Iran (Gilan Province)	–	5748	1354	19,512	3167	1122	1011	1546	Khoshnevisan et al. (2014a)
Egg plant	Iran (Gulian Province)	4.7	637	6849	5199	411	811	–	–	Nabavi-Pelesaraei et al. (2013)
Sugar beet	Turkey (Tokat Province)	163	2167	9587	19,578	115	3434	1884	–	Erdal et al. (2007)
Potato	Iran (Hamadan Province) (Machinery owners)	15,086	1049	28,435	37,951	821	2962	7620	56,024	Zanganeh et al. (2010)
Potato	Iran (Hamadan Province) (Non-machinery owners)	14,220	1044	30,079	57,972	922	3183	7056	39,607	Zanganeh et al. (2010)

Table 2 (continued)

Crop	Country (region)/climate	Energy input (MJ ha^{-1})								References
		Seed	Human	Diesel fuel	Chemical fertilizers	Biocides	Machinery	Irrigation	Electricity	
Potato	India (Bathinda district), north-western India, average annual rainfall = ~408 mm, climate-tropical steppe, semi-arid hot climate (Three row sowing method)	14,400	807	7989	15,183	2363	527	5432	10,284	Singh and Sandhu (2023)
	India (Bathinda district), north-western India, average annual rainfall = ~408 mm, climate-tropical steppe, semi-arid hot climate (Two row sowing method)	12,600	795	7201	16,068	2310	546	5236	9964	
	India (Bathinda district), north-western India, average annual rainfall = ~408 mm, climate-tropical steppe, semi-arid hot climate (Single row sowing method)	11,925	846	7760	16,486	2305	560	4877	11,260	

Table 3 Component-wise energy input in fruits crops grown in different agro-climatic regions

Crop	Country (region)/climate	Energy input (MJ ha^{-1})								References
		Seed	Human	Diesel fuel	Chemical fertilizers	Biocides	Machinery	Irrigation	Electricity	
Orange	Iran (Gulian Province)	–	851	5851	9425	599	2150	-	1559	Nabavi-Pelesaraei et al. (2013)
Nectarine	Iran (Sari region)	–	2624	7929	13,077	2234	3855	3749	5007	Qasemi-Kordkheili and Nabavi-Pelesaraei (2014)
Tangerine	Iran (Gulian Province)	–	3552	1438	18,994	501	1243	–	1650	Nabavi-Pelesaraei et al. (2014)
Apple	Greece Zagora Pelion (Central)	–	2700	16,600	7600	7300	12,800	–	–	Strapatsa et al. (2006)
Sweet cherry	Turkey (Isparta Province)	–	3082	5124	10,790	344	1124	2524	–	Demircan et al. (2006)

(13,077 MJ ha^{-1}; 33.9%), biocides (2234 MJ ha^{-1}; ~ 5.8%), irrigation (3749 MJ ha^{-1}; ~ 9.7%), and electricity (5007 MJ ha^{-1}; ~ 13.0%). Nabavi-Pelesaraei et al. (2014) conducted a study in Gulian Province, Iran, and reported that nectarine production consumed E_I of 27,873 MJ ha^{-1} with chemical fertilizers as major energy input (~ 69.4%; 18,994 MJ ha^{-1}). The second largest energy input was human labor, which accounted for ~ 13% of E_I (Table 3). According to Strapatsa et al. (2006), diesel fuel and agri-machinery were identified as the primary energy inputs in apple production in the Zagora Pelion region in Greece, representing ~ 58% of E_I. Chemical fertilizers accounted for roughly 15% of E_I, while human labor represented ~ 5%. Meanwhile, in Italy, apple cultivation utilizing the semi-intensive production system exhibited diesel fuel and fertilizers-N contribute ~ 46.4% and 20.9% of E_I, respectively (Baldini et al. 1982). Differences in planting density resulted in significant variations in energy input in apple production (Baldini et al. 1982; Strapatsa et al. 2006). Specifically, Baldini et al. (1982) observed ~ 25% higher E_I than that reported by Strapatsa et al. (2006), likely due to differences in production intensity. Strapatsa et al. (2006) planted 200 trees ha^{-1} in their study, which was approximately one-fifth of the planting density (1000 trees ha^{-1}) used in the study conducted by Baldini et al. (1982). According to Funt's (1980) apple orchards with low density and high productivity in the eastern region of USA, the major energy inputs were diesel fuel and agri-machinery, accounting for ~ 70% of E_I. Meanwhile, the energy input from chemical fertilizers was ~ 10% and biocides accounted for roughly 15% of E_I in apple production. Demircan et al. (2006) conducted a study on sweet cherry production in Isparta province, Turkey, and reported that fertilizers particularly N (~ 38.1% of E_I) were primary energy input, accounting for ~ 45.4% of E_I. The second-largest energy input was diesel fuel, constituting for ~ 21.5% of E_I. The use of biocides for plant protection had a minimal share (~ 1.5% of E_I). However, the study revealed that the pesticide usage in sweet cherry production in Isparta province was ~ 5.4-times higher than the national average in Turkey, which may lead to increased environmental risks (Table 3).

Distribution of total energy input in cereal, pulses and oilseed crops

The DE input accounts for 52 to 59% of E_I in rice production in Gulian and Golestan Provinces, Iran (Table 4). However, NRE accounts for 84–85% of E_I, while RE account for only ~ 15% (Kazemi et al. 2015). On the other hand, rice farms that utilized mechanical power in conjunction with commercial fertilizers had an equal share of RE and NRE sources (Baruah and Dutta 2007). A study conducted in Gulian Province, Iran found that in rice cultivation, DE and IDE contributed to 49 and 51% of E_I, respectively. Furthermore, RE and NRE sources contributed ~ 89 and 11% of E_I, respectively (Pishgar-Komleh et al. 2011). Singh et al. (2019a) found that approximately two-thirds of E_I in rice production in south-western Punjab, India came from DE sources, while NRE sources contributed ~ 59%. In Gorgan Province, Iran, wheat production was reported to have ~ 25% DE and 75% IDE sources, with only ~ 18% of E_I budget coming from RE sources and the remaining ~ 82% from NRE sources (Soltani et al. 2013). According to Singh et al. (2019b), wheat production in north-western India utilized approximately equal proportions of DE (52%) and IDE (48%) sources, with a significant portion of E_I (~ 78%) derived from NRE and a minor contribution (~ 22%) from RE sources (Table 4). Yousefi et al. (2014) in Kermanshah Province, Iran, reported that maize production have ~ 56% of E_I coming from DE sources and ~ 44% from IDE sources. The contribution of RE towards the E_I in maize production was ~ 13%, while NRE sources accounted for ~ 87%. Ren et al. (2012) reported that in Wendeng County, China, IDE sources accounted for a larger proportion (~ 90%) of E_I in maize cultivation, while DE sources contributed only ~ 10%. The E_I classification showed that DE and IDE sources accounted for ~ 11 and ~ 89% of E_I in maize production, respectively (Ren et al. 2012).

According to a study conducted in Adiyaman Province (Turkey), ~ 47% of E_I for cotton production comes from DE sources, while IDE sources contribute to ~ 53%. In terms of RE and NRE sources, ~ 32% of E_I comes from RE sources, while 68% comes from NRE sources (Baran 2016). In Hatay Province of Turkey, it was found that ~ 29 and 71% of E_I in cotton production were derived from DE and IDE sources, respectively. In contrast, RE and NRE sources contributed to ~ 12 and 89% of E_I, respectively (Erdal et al. 2009). The E_I in cotton production in Golestan Province, Iran was 15,184 MJ ha^{-1}, with approximately 29% of E_I coming from DE sources, while IDE accounted for ~ 71% of E_I (Sami and Rehyani, 2018). Approximately 11% of E_I in cotton production was attributed to RE sources, while the remaining ~ 89% was sourced from NRE sources. Zahedi et al. (2014) found that DE sources accounted for the majority of E_I in cotton production in Isfahan Province (Iran), with a contribution of ~ 68%. Meanwhile, RE sources contributed to ~ 32% of E_I. In contrast, in Jieshishan (Wudi County, China), only ~ 11% of E_I in cotton production was derived from DE sources, while the majority (~ 89%) came from IDE sources (Ren et al. 2012). Ren et al. (2012) found that the contribution of RE sources to the E_I was minimal, accounting for only ~ 9%, while the majority of the energy input (~ 91%) came from NRE sources.

Table 4 Classification of total input energy (E_I) as direct energy (DE) and indirect energy (IDE) and reviewable energy (RE) and non-renewable energy (NRE) use in field crops grown in different agro-climatic regions

Crop	Country (region)	Direct energy (MJ ha^{-1})[a]	Indirect energy (MJ ha^{-1})	Renewable energy (MJ ha^{-1})	Non-renewable energy (MJ ha^{-1})	References
Rice	Iran (Golestan, Gulian and Mazandaran Provinces)	32,866 (52–59)	27,659 (41–48)	9234 (15–16)	51,290 (84–85)	Kazemi et al. (2015)
Rice	Iran (Gulian Province)	19,388 (49)	19,946 (51)	4411 (11)	34,922 (89)	Pishgar-Komleh et al. (2011)
Rice	India (Mansa district, south-western Punjab)	35,200 (67)	17,200 (33)	21,400 (41)	31,000 (59)	Singh et al. (2019a)
Wheat	Iran (Gorgan Province)	3958 (25)	11,620 (75)	2864 (18)	12,715 (82)	Soltani et al. (2013)
Wheat	India (Mansa district, south-western Punjab)	13,200 (52)	12,400 (48)	5700 (22)	19,800 (78)	Singh et al. (2019b)
Maize	Iran (Kermanshah Province)	28,404 (56)	22,082 (44)	6355 (13)	44,131 (87)	Yousefi et al. (2014)
Maize	China (Wendeng, Wendeng County)	3587 (10)	33,045 (90)	3717 (11)	32,915 (89)	Ren et al. (2012)
Cotton	Turkey (Adiyaman Province)	8328 (47)	9419 (53)	5634 (32)	12,112 (68)	Baran (2016)
Cotton	Turkey (Hatay Province)	4384 (29)	10,800 (71)	1867 (12)	13,316 (88)	Erdal et al. (2009)
Cotton	Iran (Golestan), sub-humid, Mean annual temperature = 17.6 °C, Solar radiation = 15.7 MJ m^{-2} d^{-1}	10,255 (30)	24,169 (70)	3720 (11)	30,704 (89)	Sami and Reyhani (2018)
Cotton	Iran (Isfahan Province)	35,865 (68)	16,643 (32)	11,703 (22)	40,805 (78)	Zahedi et al. (2014)
Cotton	China (Jieshishan, Wudi County)	5821 (11)	46,577 (89)	4637 (9)	47,761 (91)	Ren et al. (2012)
Groundnut	Iran (Kiashahr Province)	10,849 (54)	9316 (46)	3886 (19)	16,279 (81)	Firouzi and Aminpanah (2012)
Soybean	Iran (Kordkuy county), Golestan province	13,263 (74)	4763 (26)	2487 (14)	15,539 (86)	Ramedani et al. (2011)
Sweet sorghum	China (Jieshishan, Wudi County)	5908 (22)	21,118 (78)	2143 (8)	24,946 (92)	Ren et al. (2012)
Sweet sorghum	China (Wendeng, Wendeng County)	2489 (29)	26,255 (71)	3070 (11)	28,744 (89)	Ren et al. (2012)

[a]Values in the parentheses indicate % of E_I

Firouzi and Aminpanah's (2012) reported that for groundnut production in Kiashahr Province (Iran), ~ 54% of E_I comes from DE sources, while IDE sources account for ~ 46%. Moreover, NRE sources make up ~ 81% of E_I, with RE sources accounting for only ~ 19%. On the other hand, soybean production in Golestan Province (Iran) depends on DE sources for ~ 74% of E_I, with indirect sources contributing ~ 26% (Ramedani et al. 2011). The study by Firouzi and Aminpanah (2012) found that RE sources contributed to only ~ 14% of E_I budget for groundnut production, while NRE sources accounted for the remaining 86% (Ren et al. 2012). According to a comparison of energy budgets for sweet sorghum production in Wendeng and Wudi regions of China, it was found that DE sources accounted for ~ 22–29% of E_I, while IDE sources contributed to the remaining ~ 71–78%. Additionally, RE sources accounted for only 8–11%, while NRE sources made up 89–92% of E_I for sweet sorghum production in China (Table 4).

Distribution of total energy input in vegetable and fruit crops

Except for lettuce, greenhouse and open field vegetable production predominantly relied on IDE sources. The study found that increasing energy input in greenhouse structures resulted in a polynomial increase in crop yields, as evidenced by a high coefficient of determination ($R^2 = 0.9698$) in the case of chilli cultivation in greenhouses (Kuswardhani et al. 2013). The study showed that RE sources made up only a minority share of 33–58% of E_I for both greenhouse and open field vegetable production, with NRE resources being the dominant input (Kuswardhani et al. 2013). Mohammadi-Barsari et al. (2016) found that for watermelon production, ~ 14% of E_I was derived from DE sources, while 86% was from IDE sources (Table 5). Furthermore, E_I classification for watermelon production in Kiashahr Province (Iran) revealed that only a small proportion of ~ 1.4% was contributed RE sources, while NRE sources accounted for the remaining 89%. Khoshnevisan et al. (2014a) conducted a comparison of E_I for open field and greenhouse production systems for strawberries in Gulian Province (Iran). The findings showed that the contribution of DE sources to E_I was much lower for open field production (28%) compared to greenhouse production (~ 90%). In contrast, the contribution of IDE sources was ~ 72 and 10% for open field and greenhouse production systems, respectively. Additionally, the study reported that RE sources contributed ~ 24 and 5% towards E_I in open field and greenhouse production systems, respectively. The relative contribution of NRE sources was ~ 75 and 95% for open field and greenhouse production systems, respectively. Nabavi-Pelesaraei et al. (2013) reported that in Gulian Province (Iran), eggplant production had E_I that was made up of ~ 54% DE and 46% IDE (Table 5). However, RE sources contributed only ~ 5% of E_I, while NRE sources made up the remaining ~ 95% in eggplant production. Approximately 30% of E_I in sugar beet production was attributed to DE sources, while NRE sources accounted for ~ 82% (Erdal et al. 2007).

Zanganeh et al. (2010) conducted a comparison of E_I of potato production in mechanized and non-mechanized farms in Hamadan Province (Iran). The study found that DE accounted for ~ 61 and 49% in mechanized and non-mechanized potato farms, respectively. On the other hand, IDE contributed ~ 39 and 51% of E_I in the farms of machinery owners and non-machinery owners, respectively. In terms of energy source classification, RE sources contributed ~ 16–18% of E_I, while the remaining ~ 82–84% was attributed to NRE sources. According to Khoshnevisan et al. (2013a), the majority of energy input in greenhouse cucumber production was DE sources (~ 95%), while IDE sources accounted for only ~ 5% of E_I. Additionally, RE sources contributed only a small proportion (~ 3%) of E_I, while NRE sources made up the largest proportion (~ 97%). In a study conducted by Qasemi-Kordkheili and Nabavi-Pelesaraei (2014) in Sari Province, Iran, the energy budget of nectarine was examined, and ~ 48% of E_I came from DE sources, while the remaining ~ 52% from IDE sources (Table 5). The study

Table 5 Classification of total input energy (E_I) as direct energy (DE) and indirect energy (IDE) and reviewable energy (RE) and non-renewable energy (NRE) use in vegetable and fruit crops grown in different agro-climatic regions

Crop	Country (region)	Direct energy (DE) (MJ ha^{-1})[a]	Indirect energy (IDE) (MJ ha^{-1})	Renewable energy (RE) (MJ ha^{-1})	Non-renewable energy (NRE) (MJ ha^{-1})	References
Vegetable crops						
Watermelon	Iran (Kiashahr Province)	2374 (14)	14,220 (86)	233 (1.4)	16,362 (98.6)	Mohammadi-Barsari et al. (2016)
Strawberry (open field)	Iran (Gilan Province)	9659 (28)	25,433 (72)	8382 (24)	26,710 (76)	Khoshnevisan et al. (2014a)
Strawberry (greenhouse)	Iran (Gilan Province)	1,226,734 (90)	130,199 (10)	68,942 (5)	1,287,991 (95)	Khoshnevisan et al. (2014a)
Egg plant	Iran (Gulian Province)	7487 (54)	6424 (46)	642 (5)	13,269 (95)	Nabavi-Pelesaraei et al. (2013)
Sugar beet	Turkey (Tokat Province)	11,754 (30)	26,048 (66)	5088 (13)	32,714 (82)	Erdal et al. (2007)
Potato	Iran (Hamadan Province) (*Machinery owners*)	93,127 (61)	59,944 (39)	26,878 (18)	126,193 (82)	Zanganeh et al. (2010)
Potato	Iran (Hamadan Province) (*Non-machinery owners*)	77,786 (49)	79,365 (51)	25,388 (16)	131,764 (84)	Zanganeh et al. (2010)
Fruit crops						
Nectarine	Iran (Sari region)	19,309 (48)	20,966 (52)	8173 (20)	32,102 (80)	Qasemi-Kordkheili and Nabavi-Pelesaraei (2014)
Sweet cherry	Turkey (Isparta Province)	8206 (35)	13,066 (65)	3889 (16)	17,383 (74)	Demircan et al. (2006)

[a]Values in the parentheses indicate % of E_I

also revealed that RE sources contributed to ~ 20% E_I, while NRE sources accounted for ~ 80%. Demircan et al. (2006) conducted a study on sweet cherry in Isparta Province (Turkey) and found that DE and IDE sources accounted for ~ 35 and 65% of E_I, respectively. They also reported that RE and NRE sources contributed to ~ 16 and 74% of E_I, respectively.

Energy indices for cereal, pulses and oilseed crops

Rice cultivation was energy efficient across various agro-climatic regions, with a net energy gain (NEG) ranging from 21 to 206 MJ ha^{-1} and E_R of 1.49 to 5.00 (Table 6). According to Kazemi et al. (2015), rice cultivation in Golestan, Gulian, and Mazandaran Provinces in Iran exhibited E_P of 0.064 kg MJ^{-1} and E_S of 16.7 MJ kg^{-1}. Rice production in Mazandaran Province (Iran) has shown a comparatively higher NEG of 51.8 MJ ha^{-1}, with E_P of 0.086 kg MJ^{-1} and E_S of 11.6 MJ kg^{-1} (AghaAlikhani et al. 2013). The E_R of traditional and mechanized systems in rice production has been reported as 1.72 and 1.63, respectively. Singh et al. (2019a) conducted a study in south-western Punjab (India) and reported a significantly higher NEG of 206 MJ ha^{-1} with E_P of 0.081 kg MJ^{-1}, E_S of 12.3 MJ kg^{-1}, and E_R of 5.0. In wheat production, a wide variation in NEG was observed, with the lowest value (206 MJ ha^{-1}) observed in Bangladesh (Rahman and Hasan 2014) and the highest in north-western India (166.1 MJ ha^{-1}) (Singh et al. 2019b). Table 6 shows that wheat production resulted in a NEG with E_P ranging from 0.12 to 0.27 kg MJ^{-1}, E_S ranging from 4.0 to 8.42 MJ kg^{-1}, and E_R ranging from 1.75 to 7.50. Maize production had E_R of 3.80–7.41 and E_S of 3.80–6.93 MJ kg^{-1}.

Cotton production showed a wide range of E_R (0.70–4.80) and E_S (4.99–19.2 MJ kg^{-1}). In groundnut production, a NEG of 59.1 MJ ha^{-1} was achieved with E_P of 0.212 kg MJ^{-1} and E_R of 3.93 (Firouzi and Aminpanah 2012). According to Ramedani et al. (2011), soybean cultivation in Golestan Province (Iran) resulted in a NEG of 53.1 MJ ha^{-1} with E_P of 0.16 kg MJ^{-1} and E_S of 9.86 MJ kg^{-1}. Zanganeh et al. (2010) conducted a study in Hamadan Province (Iran) to compare the E_R of potato production between mechanized and non-mechanized farms, and reported that mechanized farms achieved NEG of 4.1 MJ ha^{-1}, while non-mechanized farms resulted in a net energy loss of − 21.7 MJ ha^{-1} (Table 6).

Energy indices for vegetable and fruit crops

The E_R for various crops such as tomatoes, chilli, lettuce and strawberries in greenhouse production systems ranged from 0.12 to 0.85, with E_S consumption ranging from 0.06 to 3.07 (Table 7). Strawberry production under greenhouse systems in Guilan Province (Iran) showed the highest E_P of 20.39 kg MJ^{-1} (Khoshnevisan et al. 2014a). When comparing greenhouse and open field production systems for strawberries, open field production exhibited higher E_R (0.30) compared to greenhouse production (0.12), resulting in a higher E_S of 6.71 MJ kg^{-1} for open field and 0.06 MJ kg^{-1} for greenhouse production. According to Kuswardhani et al. (2013), tomato production under greenhouse structure had higher E_R (0.85) than open field system (0.522). The E_S was higher in open field (1.53 MJ kg^{-1}) compared to greenhouse system (0.94 MJ kg^{-1}), which resulted in lower E_P of 0.56 kg MJ^{-1} in open field and 1.06 kg MJ^{-1} in greenhouse structures. The E_R was 0.85 for tomato, 0.45 for chili in medium land, 0.49 for chili in highland, and 0.15 for lettuce in greenhouse production. In open field production, the E_R, except for lettuce, was merely half of that in greenhouse production (Kuswardhani et al. 2013).

The NEG of 19.7 MJ ha^{-1} with E_R of 2.19 was observed in watermelon production under open field system in Kiashahr Province, Iran (Mohammadi-Barsari et al. 2016). In the rain-fed watermelon production system, E_S was lower (0.87 MJ kg^{-1}) as compared to the less advanced (1.5 MJ kg^{-1}) and advanced (1.68 MJ kg^{-1}) watermelon farms in Hamadan province, Iran (Namdari 2011). According to Canakci et al. (2005), melon production in the open field system in Antalya Province, Turkey required E_S consumption of 0.97 MJ kg^{-1} of melon produced, with an E_R of 2.0. It should be noted that E_S consumption and E_R can vary based on factors such as production methods, climate conditions, and equipment and inputs used. In a study conducted by Nabavi-Pelesaraei et al. (2013), eggplant production in Gulian Province, Iran was energy efficient with NEG of 111.7 MJ ha^{-1} and E_R of 9.03. The E_S for eggplant production was 0.65 MJ kg^{-1}, which resulted in E_P of 1.53 kg MJ^{-1}. It is worth noting that E_R and E_S are influenced by various factors, including the methods used for production, climate conditions, and the type of equipment and inputs utilized. Strapatsa et al. (2006) reported that apple production had E_P of 0.42 kg MJ^{-1}, while E_S was 2.50 MJ kg^{-1}.

Maximizing the effectiveness of energy input by utilizing various agricultural inputs can enhance production efficiency (Ozkan et al. 2004). Additionally, effective management of agriculture sustainability in rural areas by promoting economic growth, profitability, and competitiveness can lead to a sustainable future for agriculture (Kuswardhani et al. 2013; Mousavi-Avval et al. 2017; Singh et al. 2019a, b). According to various studies that have utilized Data Envelopment Analysis (DEA) to optimize energy use, energy savings ranging from 3.3% (for nectarine) to 24.5% (for cucumber) have been reported (Table 8). In the case of soybean production in Golestan province of Iran, an energy saving of ~ 20% was achieved. For wheat production, an energy saving of

Table 6 Energy indices viz. energy use efficiency (or energy ratio, E_R), specific energy (E_S), energy productivity (E_P) and net energy gain (NEG) for different field crops grown in different agro-climatic regions

Crop	Country (region)	Energy use efficiency (E_R)	Specific energy (E_S) (MJ kg^{-1})	Energy productivity (E_P) (kg MJ^{-1})	Net energy gain (NEG) (GJ ha^{-1})	References
Rice	Iran (Golestan, Gulian and Mazandaran)	1.49	16.7	0.064	29.4	Kazemi et al. (2015)
Rice	Iran (Mazandaran Province) Traditional system	1.72	11.6	0.086	51.8	AghaAlikhani et al. (2013)
	Mechanized system	1.63	12.3	0.081	50.5	
Rice	India (Mansa district, south-western Punjab)	5.00	6.40	0.16	206.0	Singh et al. (2019a)
Rice	Iran (Gulian Province)	1.53	11.09	0.09	21.0	Pishgar-Komleh et al. (2011)
Wheat	Iran (Gorgan Province)	6.50	4.00	0.27	78.8	Soltani et al. (2013)
Wheat	Bangladesh (Dinajpur and Rajshahi region)	2.30	6.00	0.20	20.6	Rahman and Hasan (2014)
Wheat	Azerbaijan (West)	1.75	8.42	0.12	22.9	Taghavifar and Mardani (2015)
Wheat	India (Mansa district, south-western Punjab)	7.50	5.00	0.21	166.1	Singh et al. (2019b)
Wheat	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	2.80	5.24	–	–	Canakci et al. (2005)
Wheat	India (Himachal Pradesh) (*Low altitude*)	4.24	7.74	0.129	46.2	Mani et al. (2007)
Maize	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	3.80	3.80	–	–	Canakci et al. (2005)
Maize	India (Himachal Pradesh) (*Low altitude*)	7.41	6.93	0.14	67.2	Mani et al. (2007)
Cotton	Turkey (Hatay Province)	2.36	4.99	0.20	26.7	Erdal et al. (2009)
Cotton	Iran (Golestan), sub-humid, Mean annual temperature = 17.6 °C, Solar radiation = 15.7 Mj m^{-2} d^{-1}	1.21	9.80	0.10	7.1	Sami and Reyhani (2018)
Cotton	Iran (Isfahan Province)	0.70	19.2	0.1	–	Zahedi et al. (2014)
Cotton	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	4.80	11.2	–	–	Canakci et al. (2005)
Groundnut	Iran (Kiashahr Province)	3.93	4.74	0.212	59.1	Firouzi and Aminpanah (2012)
Sesame	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	1.50	16.2	–	–	Canakci et al. (2005)
Soybean	Iran (Golestan Province)	2.29	–	–	–	Mohammadi et al. (2013)
Soybean	Iran (Kordkuy county), Golestan Province	4.62	9.86	0.16	53.1	Ramedani et al. (2011)
Potato	Iran (Hamadan Province) (*Machinery owners*)	1.14	3.97	0.32	4.1	Zanganeh et al. (2010)
Potato	Iran (Hamadan Province) (*Non-machinery owners*)	0.95	4.72	0.27	− 21.7	Zanganeh et al. (2010)

2.6% was observed with an optimized net energy use of 2075.8 MJ^{-1}.

Greenhouse gases emissions in crop production

Table 7 Energy indices viz. energy use efficiency (or energy ratio, E_R), specific energy (E_S), energy productivity (E_P) and net energy gain (NEG) for vegetable and fruit crops grown in different agro-climatic regions

Crop	Country (region)	Energy use efficiency (E_S)	Specific energy (E_S) (MJ kg^{-1})	Energy productivity (E_P) (kg MJ^{-1})	Net energy gain (NEG) (MJ ha^{-1})	References
Greenhouse cultivation						
Tomato	Indonesia (West Java	0.85	0.94	1.06	–	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java) (*Medium land*)	0.45	1.78	0.56	–	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java) (*High land*)	0.49	1.63	0.61	–	Kuswardhani et al. (2013)
Lettuce	Indonesia (West Java	0.15	3.07	0.33	–	Kuswardhani et al. (2013)
Strawberry	Iran (Gilan Province)	0.12	0.06	20.4	–	Khoshnevisan et al. (2014a)
Open field cultivation						
Watermelon	Iran (Kiashahr Province)	2.19	0.87	1.15	19.7	Mohammadi-Barsari et al. (2016)
Watermelon	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	2.00	0.97	–	–	Canakci et al. (2005)
Melon	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	1.90	0.98	–	–	Canakci et al. (2005)
Tomato	Indonesia (West Java	0.52	1.53	0.65	–	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java) (*Medium land*)	0.18	4.56	0.22	–	Kuswardhani et al. (2013)
Chilly	Indonesia (West Java) (*High land*)	0.19	4.29	0.23	–	Kuswardhani et al. (2013)
Lettuce	Indonesia (West Java)	0.32	1.45	0.69	–	Kuswardhani et al. (2013)
Tomato	Turkey (Antalya Province) Typical Mediterranean, Dry and hot summer	0.70	1.14	–	–	Canakci et al. (2005)
Strawberry	Iran (Gilan Province)	0.30	6.71	0.16	–	Khoshnevisan et al. (2014a)
Egg plant	Iran (Gulian Province)	9.03	0.65	1.53	111.7	Nabavi-Pelesaraei et al. (2013)
Sugar beet	Turkey (Tokat Province)	25.8	–	1.53	–	Erdal et al. (2007)
Fruit crops						
nectarine	Iran (Sari region)	–	1.40	0.72	14.6	Qasemi-Kordkheili and Nabavi-Pelesaraei (2014)
Sweet cherry	Turkey (Isparta Province)	1.23	3.16	–	–	Demircan et al. (2006)

Compared to Europe and North America, major food crops in India tend to have lower GHGs emissions. For instance, GHGs emissions for cereals in Europe are typically 2–3 times higher, averaging around 2000–3000 kg CO_{2e} ha^{-1} $year^{-1}$ (Carlton et al. 2012). The levels of GHGs emissions during crop production can differ greatly among regions in Iran. For instance, wheat cultivation in Ahvaz County was associated with GHGs emissions of 903.3 kg CO_{2e} ha^{-1}, whereas corn cultivation in Kermanshah province had considerably higher emissions of 12,864.8 kg CO_{2e} ha^{-1}. It is worth noting that these values are impacted by a variety of factors such as farming techniques, soil management practices, and ecological settings, which can vary across regions (Carlton et al. 2012; Yousefi et al. 2014; Nabavi-Pelesaraei et al. 2016) (Table 9). The amount of GHGs emissions from crop production in Europe varies depending on the crop type. Potatoes were found to have higher emissions of ~ 3000 kg CO_{2e} ha^{-1} $year^{-1}$, whereas sweet peas had a lower GHGs emission of ~ 660 kg CO_{2e} ha^{-1} $year^{-1}$ (Cheng et al. 2015). Zhang et al. (2017) reported a global warming potential (GWP) of 5455 kg CO_{2e} ha^{-1} and a greenhouse gas intensity (GHGI) of 0.75 kg CO_{2e} kg^{-1} for wheat production. The literature review showed that GHGs emissions from wheat cultivation varied between 903.3 and 4997.8 kg CO_{2e} ha^{-1} in different regions (Lares-Orozco et al. 2016; Nabavi-Pelesaraei et al. 2016). The GHGs emissions for spring wheat in Canada were estimated to vary between 600 and 1400 kg CO_{2e} ha^{-1} $year^{-1}$ (Gan et al. 2012). Additionally,

Table 8 Input-wise energy saving possibilities in crop production

Crop	Country (region)/climate	Energy input (MJ ha^{-1})								Farmyard manure (FYM)	Net energy use	References
		Seed	Human	Diesel fuel	Chemical fertilizers	Biocides	Machinery	Irrigation	Electricity			
Canola	Iran (Mazandaran province)	21.2 (63.4)	350.2 (245.3)	828.9 (15.9)	792.5 (− 82.2)	–	327.2 (29.2)	–	–	186.3 (− 62.5)	(400) − 2.5	Mausai-Avval et al. (2017)
Green house cucumber	Iran (Esfahan province)	0.2 (18.2)	2967.8 (21.1)	2114.3 (23.7)	16,759.1 (26.8)	1143.5 (21.4)	168.8 (15.0)	6416.3 (26.5)	67,281.5 (15.2)	1849.6 (10.6)	407,916.3 (24.5)	Khoshnevisan et al (2013a)
Wheat	Iran (Ahvaz county)	237.2 (9.8)	23.3 (10.1)	710.7 (7.7)	909.96 (6.7)	141.0 (6.63)	83.53 (7.4)	1128.4 (12.1)	–	406.87 (23.41)	3640.9 (9.1)	Nabavi-Pelesaraei et al. (2016)
Soybean	Iran (Golestan province)	3.8 (1.5)	22.9 (6.0)	439.8 (8.9)	744.4 (8.6)	23.7 (2.6)	33.2 (3.4)	292.4 (8.7)	5556.6 (34.7)	–	7116.8 (20.1)	Mousavi-Avval et al. (2011)
Strawberry	Iran (Gilan)		814.3 (3.2)	2730.8 (21.4)	9960.2 (9.6)	987.8 (7.7)	144 (12.5)	6114.4 (25.1)	30,933.8 (8.3)	3635 (18.7)	273,902.8 (20.2)	Khoshnevisan et al. (2014a)
Wheat	Iran (Esfahan province)	75.1 (1.9)	3.1 (1.9)	153.7 (4.3)	1400.1 (6.0)	16.8 (9.6)	37.8 (2.0)	20.5 (0.3)	131.2 (0.3)	237.6 (17.9)	2075.8 (2.6)	Khoshnevisan et al. (2013a)
Orange	Iran (Guilan province)	–	66.8 (7.6)	1046 (17.9)	1197 (8.5)	81.2 (13.6)	279 (13.0)	–	613 (39.3)	29.9 (5.6)	3314 (12.9)	Nabavi-Pelesaraei et al (2013)
Nectarine	Iran (Sari region)	–	101 (3.9)	291 (3.7)	217 (1.7)	102 (4.6)	72 (1.9)	154 (4.1)	325 (6.5)	46 (2.6)	1309 (3.3)	Nabavi-Pelesaraei et al (2013)

Röös et al. (2011) reported a GHGI of 0.2–0.6 kg CO_{2e} kg^{-1} for wheat production in Sweden.

A research study carried out in the Golestan province of Iran revealed that chemical fertilizers were the primary cause of GHGs emissions in wheat cultivation, emitting an average of 1233.0 kg CO_{2e} ha^{-1} (Table 9). Diesel fuel was the second highest contributor to emissions in wheat cultivation, accounting for 390.3 kg CO_{2e} ha^{-1}. For rice cultivation, GHGs emissions were approximately 6094.1 kg CO_{2e} ha^{-1} (Mohammadi et al. 2014), The study conducted in the Golestan province of Iran revealed that barley cultivation resulted in lower GHGs emissions, with an average of 1105.7 kg CO_{2e} ha^{-1}. On the other hand, soybean cultivation showed a wider range of emissions, ranging from 957 to 1971.4 kg CO_{2e} ha^{-1}, depending on the specific practices employed (Yousefi et al. 2014; Mohammadi et al. 2014, 2013). In China, rice cultivation has a GWP of 2472.3 kg CO_{2e} ha^{-1} and a GHGI of 0.4 kg CO_{2e} kg^{-1} (Cheng et al. 2015). Zhang et al. (2017) conducted a study in northeastern China and found that the GWP of rice cultivation was higher than previously reported, with emissions of 11,881 kg CO_{2e} ha^{-1} and a GHGI of 1.6 kg CO_{2e} kg^{-1} rice grains. Interestingly, the study also found that GHGs emissions were higher in broadcasted rice (1112.1 kg CO_{2e} ha^{-1}) compared to transplanted rice (1051.7 kg CO_{2e} ha^{-1}) in the same region Thialand (Soni et al. 2013). Corn cultivation showed a variable GWP across different studies, ranging from 781.2 kg CO_{2e} ha^{-1} (Cheng et al. 2015) to 4052 kg CO_{2e} ha^{-1} in China (Zhang et al. 2017) with GHGI of 0.12 and 0.48 kg CO_{2e} kg^{-1}, respectively. It has been observed that rice paddies are a significant contributor to atmospheric methane (CH_4) emissions. Specifically, the emissions of CH_4 from wetland paddy fields make up approximately 10–20% of the total global CH_4 emissions, which range from 50 to 100 Tg $year^{-1}$ (Reiner and Mikha, 2000). Studies have shown that changes in water management practices in rice production can significantly reduce CH_4 emissions. Specifically, the reduction in CH_4 emissions has been linked to the modification of water management techniques (Liu et al. 2010; Nayak et al. 2015; Yan et al. 2005; Singh and Benbi 2020a). By optimizing drainage and manure management practices, it is feasible to both reduce CH_4 emissions and increase crop yield simultaneously (Banerjee et al. 2002; Malla et al. 2005; Thu et al. 2016).

According to Khoshnevisan et al. (2013a), the GHGs emissions from cucumber production in Esfahan province of Iran were 45,177.3 kg CO_{2e} ha^{-1}, with electricity accounting for ~ 50% of the total emissions, followed by chemical fertilizers, diesel fuel, biocides, and machinery. In comparison, greenhouse strawberry cultivation had ~ 44% higher emissions (35,083.5 kg CO_{2e} ha^{-1}) than open field strawberry cultivation (803.4 kg CO_{2e} ha^{-1}), with GHGI of 0.2 and 0.06 kg CO_{2e} kg^{-1}, respectively (Khoshnevisan

Table 9 Carbon dioxide equivalent (CO_{2e}) emissions and environmental indices of crop production

Crop	Country (region)/Climate	Greenhouse gases (GHGs) emission (kg CO_{2e} ha^{-1})								References
		Electricity	Diesel fuel	Fertilizer-N	Biocides	Farm-yard manure (FYM)	Machinery	GWP[a] (kg CO_{2eq} ha^{-1})	GHGI[b] (kg CO_{2e} kg^{-1})	
Wheat	Iran (Gorgan)	–	344.8	529.7	32.8	–	181.6	1137.0	0.29	Soltani et al. (2013)
Wheat	Iran (Ahvaz county)	–	510.8	256.7	46.7	–	–	903.3		Nabavi-Pelesaraei et al. (2016)
Wheat	Iran (Golestan province)	167.7	455.2	271.7	–	21.7	–	1171.1	–	Mohammadi et al. (2014)
Wheat	Mexico (Yaqui valley)	–	917.9	3873.8	38.8	–	–	4997.8	0.76	Lares-Orozco et al. (2016)
Rice	Iran (Golestan province)	973.1	564.8	626.3	–	–	–	6094.1	–	Mohammadi et al. (2014)
Barley	Iran (Golestan province)	152.0	435.5	250.9	–	22.5	–	1105.7	–	Mohammadi et al. (2014)
Corn	Iran (Kermanshah province	9858.3	807.4	2199.2	–	–	–	12,864.8	1.40	Yousefi et al. (2014)
Canola	Iran (Golestan province)	123.5	363.2	290.4	–	8.8	–	1063.5	–	Mohammadi et al. (2014)
Soyabean	Iran (Golestan province)	899.7	392.8	179.8	–	23.5	–	1791.4	–	Mohammadi et al. (2014)
Soyabean	Iran (Golestan province)	301.0	104.0	524.0	26.0	–	–	957.0	–	Mohammadi et al. (2013)

[a] *GWP* Global warming potential

[b] *GHGI* Greenhouse gas intensity

et al. 2014a). Pergola et al. (2013) reported that conventional lemon and orange cultivation had significantly higher GHGs emissions and lower GHGI than organic cultivation. In greenhouse strawberry cultivation, electricity was the main source of GHGs emissions, accounting for ~ 54% of the total, while in open field cultivation, chemical fertilizers contributed ~ 46.1% (Khoshnevisan et al. 2014a). In greenhouse cultivation, natural gas was the second largest contributor to GHGs emissions, accounting for ~ 38.8%, while biocides were the second largest contributor in open field conditions (~ 24.1%) (Khoshnevisan et al. 2014a) (Table 9).

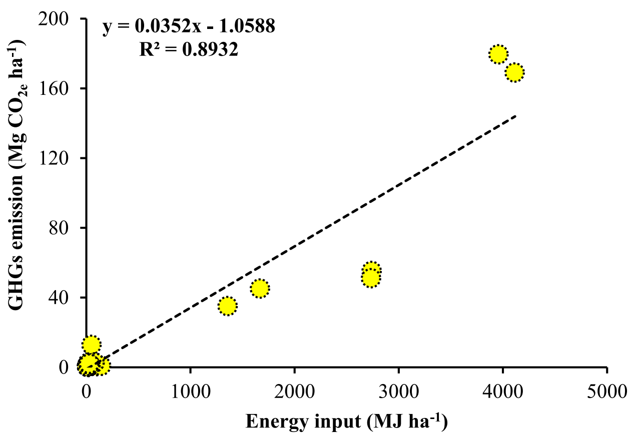

Fig. 4 Relationship of energy input (MJ ha^{-1}) and greenhouse gases emissions (Mg CO_{2e} ha^{-1}) (data points are taken from studies of Soltani et al. 2013; Khoshnevisan et al. 2014a; Nabavi-Pelesaraei et al. 2016; Mohammadi et al. 2014; Lares-Orozco et al. 2016; Zhang et al. 2017; Cheng et al. 2015; Yousefi et al. 2014; Khoshnevisan et al. 2013a)

Mitigation potential of greenhouse gases emissions

Figure 4 shows a linear relationship between GHGs emissions and E_I in crop production. Several researchers applied different optimization techniques for enhancing energy efficiency in crop production and reducing GHGs emissions in different cropland ecosystems (Tables 10 and 11). Qasemi-Kordkheili and Nabavi-Pelesaraei (2014) reported ~ 3.6% reduction (from 1266 to 1221 kg CO_{2e} ha^{-1}) in GHGs emissions for nectarine after DEA based optimization (Table 11). For cucumber grown in Esfahan province of Iran, Khoshnevisan et al. (2013a) reported a significant reduction in GHGs emissions from 45,177.3 to 10,181.4 kg CO_{2e} ha^{-1} (by ~ 77.5%) under optimized conditions using DEA approach. In wheat grown in Khuzestan province of Iran, Nabavi-Pelesaraei et al. (2016) found a total GHGs emission of 903.3 kg CO_{2e} ha^{-1}, with reductions of ~ 7.3 and 62.3% under optimized conditions using DEA and multi-objective genetic algorithm (MOGA), respectively. Mohammadi et al. (2013) reported a reduction of ~ 11.5% in GHGs emissions for soybean, from 957 to 847 kg CO_{2eq} ha^{-1} under optimized conditions using DEA.

Artificial intelligence for predicting yields and environmental impacts of crop production

Artificial intelligence (AI) has been widely used to predict crop yields based on energy units which have largely helped in energy optimization and reduce costs (Table 12). Artificial neural networks (ANNs) and adaptive neuro-fuzzy inference systems (ANFIS) have become

Table 10 Carbon dioxide equivalent (CO_{2e}) emissions and environmental indices of in vegetable crop production

Crop	Country (region)/ climate	Greenhouse gases (GHGs) emission (kg CO_{2e} ha^{-1})							References
		Electricity	Diesel fuel	Fertilizer-N	Biocides	Natural gas	Machinery	GWP[a] (kg CO_{2e} ha^{-1})	
Cucumber	Iran (Esfahan province)	22,572	514.8	1181	455.9	–	–	–	Khoshnevisan et al. (2013a)
Strawberry (Open field)	Iran (Gilan province)	78.8	78.2	370.1	196.7	–	79.6	803.4	Khoshnevisan et al. (2014a)
Strawberry (Greenhouse)	Iran (Gilan province)	18,962	738.2	1493	201.7	13,607	82	35,083	Khoshnevisan et al. (2014a)

[a]*GWP* global warming potential

Table 11 Optimization techniques and carbon dioxide equivalent emissions (CO_{2e}) and environmental indices viz. global warming potential (GWP) and greenhouse gases intensity (GHGI) of crop production system (CPS) under current and optimized production system (OPS)

Crop	Country (region)/ climate	Optimization technique[a]	Production system	Carbon dioxide equivalent emissions (kg CO_{2e} ha^{-1})							GWP (Mg CO_{2e} ha^{-1} $year^{-1}$)	References
				Diesel	Chemical fertilizers	Biocides	Electricity	Field operations	Machinery	Natural gas		
Nectarine	Iran (Sari region)	DEA	CPS	389.0	247.7	100.8	255	–	274	–	1266	Qasemi-Kordkheili and Nabavi-Pelesaraei (2014)
			OPS	374.0	242.8	96.1	239	–	269.0	–	1221	
Strawberry (open field)	Iran (Gilan province)	DEA	CPS	738.2	1492.8	201.7	18,962	–	82.0	13,607	35,083	Khoshnevisan et al. (2014a)
			OPS	580.6	1337.2	138.8	17,386	–	0.7	9866	29,309	
Wheat	Iran (Esfahan province)	DEA	CPS	206.0	371.2	8.0	2005	–	134.6		27,245	Khoshnevisan et al. (2013b)
			OPS	197.1	349.9	7.3	1998	–	132.0		2684	
Cucumber	Iran (Esfahan province)	DEA	CPS	514.8	2492	455.9	22,572	416.4	–	18,726	45,177	Khoshnevisan et al. (2013a)
			OPS	392.8	1903.2	132.0	19,143	0.4			10,181	
Wheat	Iran (Khuzestan province)	DEA and MOGA	CPS	510.8	256.7	46.7	–	–	80.2	–	903	Nabavi-Pelesaraei et al. (2016)
			OPS (DEA)	471.7	247.9	43.6	–	74.3	–		837	
			OPS (MOGA)	56.1	193.1	30.7		60.0			340	
Soyabean	Iran (Golestan province)	DEA	CPS	–	524.0	26.0	–	104.0			957	Mohammadi et al. (2013)
			OPS	–	487	26	–	103			847	

[a] *DEA* data envelopment analysis, *MOGA* multi-objective genetic algorithm

Table 12 Artificial intelligence tools viz. artificial neural networks (ANNs) and artificial neuro-fuzzy inference system (ANFIS) for prediction of yield of agricultural crops based on energy inputs

Study details	Type of artificial intelligence tool applied	Best results		References
Artificial intelligence for predicting wheat grain yield in Isfahan region, Iran	ANN and ANFIS	*Wheat grain yield* ANFIS: R = 0.919, RMSE = 0.083, MAPE (%) = 0.8	*Wheat grain yield* ANN: 11-32-10-1 topology, R = 0.92, RMSE = 0.1, MAPE (%) = 0.9	Khoshnevisan et al. (2014b)
Artificial intelligence for environmental impact assessment of cucumber and tomato in Isfahan region, Iran	ANFIS	*Cucumber yield* R = 0.960–998, RMSE = 0.014–0.021, MAPE (%) = 0.1–0.8	–	Khoshnevisan et al. (2013b)
		Tomato yield R = 0.965–0.999, RMSE = 0.003–0.021, MAPE (%) = 0.04–0.8	–	
		ANFIS; R^2 = 0.370–0.944, RMSE = 0.114–0.689, MAPE (%) = 0.021–0.076 ANN; 7–9-6–11 topology, R^2 = 0.923–0.986		
		Abiotic depletion ANFIS; R^2 = 0.409–0.954, RMSE = 0.153–0.652, MAPE (%) = 0.057–0.114		
		Acidification ANFIS; R^2 = 0.293–0.964, RMSE = 0.161–0.641, MAPE (%) = 0.018–0.087		
		Eutrophication ANFIS; R^2 = 0.471-.956, RMSE = 0.112–0.619, MAPE (%) = 0.017–0.114		
		Global warming potential ANFIS; R^2 = 0.203–0.975, RMSE = 0.129–0.696, MAPE (%) = 0.033–0.103		
Artificial intelligence for prediction of output energy and environmental impacts of sugarcane production in Khuzestan province, Iran	ANN and ANFIS	*Output energy*	*Output energy* ANN; 7-9-6-11 topology, R^2 = 0.923–0.986	Kaab et al. (2019)

Table 12 (continued)

Study details	Type of artificial intelligence tool applied	Best results		References
Artificial intelligence for environmental impact assessment of open field and green-house strawberry production in Guilan province, Iran	ANN and ANFIS	*Abiotic depletion* ANFIS; $R^2=0.97$, RMSE = 0.07, MAPE (%) = 2.55	*Abiotic depletion* ANN; $R^2=0.95$, RMSE = 0.11, MAPE (%) = 2.99	Khoshnevisan et al. (2013c)
		Acidification ANFIS; $R^2=0.97$, RMSE = 0.06, MAPE (%) = 5.83	*Acidification* ANN; $R^2=0.84$, RMSE = 0.17, MAPE (%) = 8.95	
		Eutrophication ANFIS; $R^2=0.99$, RMSE = 0.04, MAPE (%) = 2.34	*Eutrophication* ANN; $R^2=0.87$, RMSE = 0.15, MAPE (%) = 5.13	
		Global warming potential ANFIS; $R^2=0.98$, RMSE = 0.06, MAPE (%) = 0.65	*Global warming potential* ANN; $R^2=0.85$, RMSE = 0.15, MAPE (%) = 0.11	
		Ozone layer depletion ANFIS; $R^2=0.98$, RMSE = 0.04, MAPE (%) = 0.38	*Ozone layer depletion* ANN; $R^2=0.85$, RMSE = 0.12, MAPE (%) = 0.75	
		Photochemical oxidation ANFIS; $R^2=0.98$, RMSE = 0.05, MAPE (%) = 1.79	*Photochemical oxidation* ANN; $R^2=0.90$, RMSE = 0.13, MAPE (%) = 3.04	
Fuzzy based artificial intelligence for evaluation of traditional and consolidated rice farms in Guilan province, Iran	ANFIS	*Abiotic depletion* ANFIS; $R^2=0.944$, RMSE = 0.007, MAPE (%) = 0.07	–	Khoshnevisan et al. (2014c)
		Acidification ANFIS; $R^2=0.990$, RMSE = 0.11 MAPE (%) = 0.14	–	
		Eutrophication ANFIS; $R^2=0.983$, RMSE = 0.009, MAPE (%) = 0.52	–	
		Global warming potential ANFIS; $R^2=0.996$, RMSE = 0.004, MAPE (%) = 0.02	–	
		Ozone layer depletion ANFIS; $R^2=0.982$, RMSE = 0.991 MAPE (%) = 0.003	–	
		Photochemical oxidation ANFIS; $R^2=0.968$, RMSE = 0.005, MAPE (%) = 0.10	–	

Table 12 (continued)

Study details	Type of artificial intelligence tool applied	Best results		References
Multi-layer adaptive neuro-fuzzy inference system for estimation of greenhouse strawberry yield in Guilan province, Iran	ANN and ANFIS	*Strawberry yield* ANFIS; R^2 = 0.265–0.963, MAE = 0.014–0.061, RMSE = 0.017–0.074, MAPE (%) = 0.003–0.011	*Strawberry yield* ANN; 8-18-12-1 topology; R2 = 0.912; MAE = 0.039; MAPE = 0.0084; RMSE = 0.067	Khoshnevisan et al. (2014c)
Potato yield based on energy inputs using multi-layer adaptive neuro-fuzzy inference system in Isfahan province, Iran	ANN and ANFIS	*Potato tuber yield* ANFIS; R^2 = 0.731–0.950, RMSE = 0.057–0.124, MAPE (%) = 0.400–1.000	*Potato tuber yield* ANN; 22-30-2-1 topology; R2 = 0.925; MAPE = 0.071; RMSE = 0.5	Khoshnevisan et al. (2014d)
Artificial intelligence methods and life cycle assessment to predict energy output and environmental impacts of paddy production in Guilan province, Iran	ANN and ANFIS	*Potato tuber yield* ANFIS; R^2 = 0.237–0.860, RMSE = 8911–16,904, MAPE (%) = 18.7–32.0 *Abiotic depletion* ANFIS; R^2 = 0.160–0986, RMSE = 0.31–1.44, MAPE (%) = 7.02–41.0 *Acidification* ANFIS; R^2 = 0.506–0.995, RMSE = 0.74–6.37, MAPE (%) = 5.15–48.7 *Eutrophication* ANFIS; R^2 = 0.451–0997, RMSE = 0.19–2.43, MAPE (%) = 4.30–60.4 *Global warming potential* ANFIS; R^2 = 0.693–0.989, RMSE = 67.9–377.8, MAPE (%) = 6.59–44.9 *Photochemical oxidation* ANFIS; R^2 = 0.693–0.985, RMSE = 0.01–0.38, MAPE (%) = 7.23–148.6	*Potato tuber yield* ANN; 12-6-8-1 topology; R^2 = 0.912, RMSE = 7375, MAPE (%) = 13.0 *Abiotic depletion* ANN; 12-6-5-1, R^2 = 0.999, RMSE = 0.0036, MAPE (%) = 0.10 *Acidification* ANN; 12-6-5-1 topology, R^2 = 0.999, RMSE = 0.003, MAPE (%) = 0.03 *Eutrophication* ANN; 12-5-7-1, R^2 = 0.999, RMSE = 0.0040, MAPE (%) = 0.10 *Global warming potential* ANN; 12-10-9-1, R^2 = 0.999, RMSE = 0.012, MAPE (%) = 0.0011 *Photochemical oxidation* ANN; 12-6-6-1, R^2 = 0.998, RMSE = 0.0034, MAPE (%) = 4.14	Nabavi-Pelesaraei et al. (2018)

R correlation coefficient, R^2 Coefficient of determination, *RMSE* root mean square error, *MAPE* mean absolute percentage error; *MAE* mean absolute error increasingly popular AI tools in the prediction of yields and environmental impacts in a wide range of fields such as agriculture, water resources management, and industrial processes (Khoshnevisan et al. 2014b, c, d). ANNs have also been used to predict environmental impacts and nutrient leaching from agricultural fields (Dikshit et al. 2015). Specifically, ANFIS outperformed ANN in all cases, with higher ‘r’ values and lower RMSE and MAPE values (Khoshnevisan et al. 2014b, c, d). These findings suggest that ANFIS models are a more accurate method for predicting crop yields and their environmental impacts based on energy inputs than ANN models (Table 12).

Conclusions

The intricate relationship between water, energy, and the environment underscores the critical importance of optimizing agricultural practices to ensure crop production, ecosystem sustainability, and food security. In different cropland ecosystems, chemical fertilizers and irrigation emerged as a significant contributor to both water and energy footprints, which in turn profoundly influence C emissions and ecosystem health. Notably, the reliance on NRE sources remains high, particularly in the cultivation of field crops, while the varying E_R across different crops highlight the necessity for tailored interventions. The linear correlation between GHGs emissions and E_I emphasizes urgency of optimizing production techniques to mitigate environmental impacts. Data envelopment analysis can help in energy saving by optimizing input use without any risk of yield loss. Consequently, the implementation of advanced technological frameworks, such as ANNs and ANFIS presents a promising avenue for researchers and policymakers for crop yield prediction. By harnessing these tools, stakeholders can devise effective strategies to enhance resilience within agro-ecosystems and promote long-term environmental sustainability, ultimately leading to a more sustainable agricultural future. Nonetheless, to address the high water footprints and associated energy consumption in crop production, dissemination of efficient irrigation water management technologies is crucial. Furthermore, there is a need to promote the efficient use of chemical fertilizers which contribute to a significant proportion of energy input and C footprints in crop production. Sustainable nutrient management, particularly for fertilizer-N, is essential to address the N paradox.

Declarations

Conflict of interest The authors declare no competing interests.

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