# Effects of tillage and irrigation method on energy use and greenhouse gas emissions of corn production

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**Abstract:** In this study, the effect of tillage and irrigation method on energy use, energy output, energy use efficiency (EUE), net energy gain (NEG), specific energy (SE), energy productivity (EP), and greenhouse gas (GHG) emissions of corn production was evaluated. The research was conducted in a split plot design with three replicates in Fars province, Iran. Main plots were irrigation methods including surface irrigation (SI) (gated pipe), drip irrigation (DI), and sprinkler irrigation (SPI). Tillage methods including no-till (NT), reduced tillage (RT), and conventional tillage (CT) were considered as sub plots. Results showed that irrigation method had significant effect on energy use, energy output, energy use efficiency, net energy gain, specific energy, energy productivity, and greenhouse gas (GHG) emissions of corn production, while tillage method had significant influence only on energy use, energy output, and net energy gain. SI had the highest input energy (165856 MJ ha$^{-1}$) and GHG emission (29376 kg $CO_2$e ha$^{-1}$) followed by SPI (117662 MJ ha$^{-1}$ and 20363 kg $CO_2$e ha$^{-1}$) and DI (88597 MJ ha$^{-1}$ and 15025 kg $CO_2$e ha$^{-1}$). DI and SPI reduced input energy by 45% and 29% and GHG emissions by 48.9% and 30.7%, respectively compared to SI. NT reduced the energy input and increased the energy output by 2.3% and 9.8% respectively, compared to the CT. Results of this study also showed that corn production cropping system involving an efficient irrigation method (DI) and conservation tillage (CoT) would be an energy efficient cropping system with low environmental pollution risks.

**Keywords:** energy use efficiency, net energy gain, specific energy, energy productivity, irrigation water, output energy, tillage methods

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## 1 Introduction

Different types of input energies are consumed in production of agriculture crops and some output energies are produced in this process. Input energy required for agriculture production can be divided into direct and indirect or renewable and non-renewable energy forms (Rafiee et al., 2010). On the other hand, energy use in crop production is necessarily accompanying with some greenhouse gas (GHG) emissions which are big risk for environment. Therefore, energy balance and GHG emission in agricultural crop production should be monitored and controlled to reduce the environmental risks and global warming problems. Energy indices such as energy efficiency, net energy gain, specific energy, and energy productivity are the most common indicators of energy balance in agricultural crop production.

Output to input ratio of 0.76 was calculated for maize in Bursa province, Turkey of which fertilizers with 51.47% had the highest share followed by fuel and electricity (Vural and Efecan, 2012). Energy intensity for corn grain in Ontario, Canada was reported from 1.75 to

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2.17 GJ $Mg^{-1}$ and grain drying with 33% had the largest proportion in consumed energy followed by nitrogen fertilizer and diesel fuel (Jayasundara et al., 2014). Grassini and Cassman (2012) reported values of 30 GJ $ha^{-1}$ and 159 GJ $ha^{-1}$ for input and output energy, respectively for irrigated maize production in Nebraska. Irrigation operation energy for maize production in Mexico ranged from 1.0 to 31.6 GJ $ha^{-1}$ depending on the irrigation system used (Juárez-Hernández and Pardo, 2019). Values of 34.640 MJ $ha^{-1}$, 102.973 MJ $ha^{-1}$, 2.97, 0.20 kg $MJ^{-1}$, and 68.333 MJ $kg^{-1}$ were respectively reported for input energy, output energy, energy use efficiency, energy productivity, and net energy gain of corn production in Khuzestan province, Iran (Lorzadeh et al., 2012). Banaeian and Zangeneh (2011) found that average input energy increased from 40.98 GJ $ha^{-1}$ in 2001 to 63.64 GJ $ha^{-1}$ in 2007 and average output energy increased from 89.03 GJ $ha^{-1}$ in 2001 to 107.54 GJ $ha^{-1}$ in 2007 for corn production in Iran. Houshyar et al. (2012) reported an average input energy of 42918 MJ $ha^{-1}$ for corn production in Fars province, Iran.

About 20% of world total net GHG emissions come from the agricultural sector (Sims and Flammini, 2014) and Australia emits the highest per-capita GHG in the world (Chen et al., 2015). Electricity which is basically used for water pumping and operating stationary systems is the highest greenhouse gas emitter in Australia (Chen et al., 2015). Jayasundara et al. (2014) reported the range of 243 to 353 kg $CO_2$eq $Mg^{-1}$ for GHG emission intensity of grain corn production in Ontario, Canada which most of that were associated with N inputs. Irrigation operation related GHG emissions for maize production in Mexico ranged from 62.0 to 2019.9 kg $CO_2$e $ha^{-1}$ depending on the irrigation system used (Juárez-Hernández and Pardo, 2019). Grassini and Cassman (2012) reported value of 231 kg $CO_2$e $Mg^{-1}$ for GHG emission intensity for irrigated maize production in Nebraska. GHG emission from summer corn grain increased with N-fertilizer application rate in the North China Plain and N-fertilizer had the highest share in the total GHG emission followed by electricity for pumping irrigation water (Wang et al., 2015). Adom et al. (2012) reported GHG emission intensity of 390 g $CO_2$e $kg^{-1}$ of dry corn grain production in the USA. Qi et al. (2018) reported the total GHG emissions ranging from 3152.9 to 4557.2 kg $CO_2$eq $ha^{-1}$ for corn production in the Loess Plateau, China depending on cultivation patterns. Ma et al. (2012) showed that high N application increased total GHG emissions in maize production under continuous maize monoculture, maize following forage legumes, and grain legumes.

Energy use and GHG emissions in agricultural crops production may also affected by irrigation systems, tillage methods, and planting systems. On-farm energy consumption for crop production usually depends on tillage methods, irrigation type, water source, depth of ground water, soil type, and pump types (Chen et al., 2015). Chen and Baillie (2009) found that moving from CT to minimum tillage can save approximately 10% of the overall fuel used on the farm. Chen et al. (2015) reported that energy requirement for grain crops production under zero tillage was less than that of CT in dryland cropping condition of Australia. Baillie (2009) found that the RT and NT operations saved energy for 12% and 24%, respectively compared to the CT in Northern NSW, Australia. Behnke et al. (2018) showed that methane ($CH_4$) emissions were not affected by tillage method and crop rotation, but crop rotation had significant effect on cumulative carbon dioxide ($CO_2$) emissions during corn production in Illinois, USA. Maraseni and Cockfield (2011) proved that the net effect of switching from CT to NT on GHG emissions in Queensland, Australia was positive but relatively small. Sainju et al. (2012) found that $CO_2$ and $N_2O$ fluxes were higher in CT with N fertilization under the irrigated condition than those of NT with and without N fertilization under irrigated and non-irrigated conditions in malt barley production. Oo et al. (2018) found that planting method had significant effect on methane ($CH_4$) and ($N_2O$) emissions during rice production, while $CH_4$ and $N_2O$ emissions were not affected by rice varieties. Comparing RT and CT effects on $N_2O$ and $CH_4$ emissions in a grass-clover ley-winter wheat-cover crop sequence in Switzerland showed that tillage system had no significant impact on cumulative $N_2O$ and $CH_4$ emissions (Krauss et al., 2017).

According to the results found in literature, tillage and irrigation methods could affect energy consumption and GHG emissions during agricultural crops production, but these effects depend on soil type, climate conditions, and crops type. On the other hand, effects of interaction between tillage and irrigation methods on energy use and GHG emissions have not yet been investigated. Therefore, effects of tillage and irrigation methods on GHG emissions, energy use, energy output, energy use efficiency, net energy gain, specific energy, and energy productivity of corn were evaluated in this study.

## 2 Materials and methods

### 2.1 Site specifications

The study was carried out in Marvdasht region of Fars province located in Southern Iran (30°94′E and 52°48′N) with average annual rainfall of 365 mm, maximum temperature of 41°C, minimum temperature of 9°C, and altitude of 1620 m above mean sea level from 2009 to 2011. Specifications of the soil (Typic Calcixerepts) in which the study was performed are presented in Table 1.

**Table 1 Selected properties of the soil used for the study**

| Soil depth (m) | O.C (%) | EC (dS m$^{-1}$) | pH | Bulk density (g cm$^{-3}$) | Hydraulic Conductivity (cm day$^{-1}$) | Clay (%) | Silt (%) | Sand (%) | Soil texture |
|---|---|---|---|---|---|---|---|---|---|
| 0.00-0.10 | 0.72 | 0.94 | 8.22 | 1.24 | 24.9 | 42.00 | 34.00 | 24.00 | Clay |
| 0.10-0.20 | 0.70 | 0.84 | 8.20 | 1.30 | 16.1 | 45.00 | 44.00 | 11.00 | Silty-clay |

### 2.2 Treatments

This research was conducted in a split plot experimental design with three replicates in Fars province, Iran. Main plots in this research were irrigation methods including 1) surface irrigation (SI), 2) drip tape irrigation (DI), and 3) sprinkler irrigation (SpI). Tillage methods including no-till (NT), reduced tillage (RT), and conventional tillage (CT) were considered as sub plots. In the CT, primary tillage was performed using a moldboard plow and secondary tillage operation was done using a disk harrow and land leveler. Seed bed was prepared in the RT using a tine and disc cultivator which was able to complete the primary and secondary tillage operations simultaneously. Corn seeds were directly planted using SEMEATO (SEMEATO Factories, Passo Fundo, Brazil) direct planter without any seed bed preparation in the NT. Corn variety of 704 single cross with the seed rate of 25 kg ha$^{-1}$ was planted with the row space of 0.75 m in early July and harvested in early November. The study was conducted for two years (2009-2011) and average of two years data was used in this paper.

### 2.3 Energy indices

Sources of input energy (IE) for producing corn were human labour, machineries, electricity for pumping irrigation water, irrigation water, fertilizers, seeds, chemicals (herbicides and pesticides), transportation, and fuel. Output energy (OE) source was corn grain; therefore, OE was determined by multiplying corn grain yield by the energy equivalent of produced product. IE were obtained by multiplying the amount of input used by the energy equivalent of that specific input shown in Table 2. Input energy related to the machineries was obtained using the following equation (Kitani et al., 1999):

$$ME = \frac{M \times E}{T \times C_a} \tag{1}$$

Where $ME$ is the share of energy consumed for manufacturing of the machine used in producing crop (MJ ha$^{-1}$), $T$ is machine lifespan (hr), $C_a$ is the machine effective field capacity (ha hr$^{-1}$), $M$ is the machine weight (kg), and $E$ is the equivalent energy of material used in machine (MJ kg$^{-1}$). Energy consumption in irrigation systems included both direct energy (DE) use and indirect energy (IE) use. Direct energy was consumed to lift or pressurize the water required by crop and calculated using the following equation (Kitani et al., 1999)

$$DE = \frac{Q \times \rho \times g \times h}{\eta_1 \eta_2 \times 10^6} \tag{2}$$

Where $DE$ is direct energy consumed for water supply (MJ ha$^{-1}$), $\rho$ is water density (kg m$^{-3}$), $g$ is gravity acceleration (m s$^{-2}$), $Q$ is total water supplied to the crop during the growing season ($m^3$ $ha^{-1}$), *h* is pumping dynamic head (m), $\eta_1$ is pumping efficiency (0.8), and $\eta_2$ is efficiency of energy converting which was considered 0.2 for the electro-pumps. 18% of direct-use energy was considered for the indirect energy consumption in irrigation process which was included raw materials, manufacturing, and transportation of elements used in irrigation system (Kitani et al., 1999).

**Table 2 Energy equivalent of different inputs**

| Input | Energy equivalent | Reference | Input | Energy equivalent | Reference |
|---|---|---|---|---|---|
| Diesel | 47.8(MJ $L^{-1}$) | (Kitani et al., 1999) | Nitrogen | 78.1(MJ $kg^{-1}$) | (Kitani et al., 1999) |
| Tractor | 138(MJ $kg^{-1}$) | (Kitani et al., 1999) | Phosphate | 17.4(MJ $kg^{-1}$) | (Kitani et al., 1999) |
| Combine | 116(MJ $kg^{-1}$) | (Kitani et al., 1999) | Potash | 13.7(MJ $kg^{-1}$) | (Kitani et al., 1999) |
| Plough | 180(MJ $kg^{-1}$) | (Kitani et al., 1999) | Chemicals | 85.5(MJ $L^{-1}$) | (Kitani et al., 1999) |
| Disk harrow | 149(MJ $kg^{-1}$) | (Kitani et al., 1999) | Transportation | 3 (MJ $t^{-1}$.$km^{-1}$) | (Kitani et al., 1999) |
| Land leveller | 133(MJ $kg^{-1}$) | (Kitani et al., 1999) | Electricity | 12 (MJ $kWh^{-1}$) | (Kitani et al., 1999) |
| Seed planter | 133(MJ $kg^{-1}$) | (Kitani et al., 1999) | Corn grain | 15(MJ $kg^{-1}$) | (Franzluebbers and Francis, 1995) |
| Sprayer | 129(MJ $kg^{-1}$) | (Kitani et al., 1999) | Corn seed hybrid | 100 (MJ $kg^{-1}$) | (Kitani et al., 1999) |
| Labour | 1.96(MJ $h^{-1}$) | Pishgar Komleh et al., 2011) | Irrigation water | 1.02 (MJ $m^{-3}$) | (Shahin et al., 2008) |

After determining input energy (IE) and output energy (OE), energy indices including energy use efficiency (EUE), net energy gain (NEG), specific energy (SE), and energy productivity (EP) were obtained using the following equations:

$$EUE = \frac{OE}{IE} \tag{3}$$

$$NEG = OE - IE \tag{4}$$

$$SE = \frac{IE}{Y} \tag{5}$$

$$EP = \frac{Y}{IE} \tag{6}$$

Where *EUE* is energy use efficiency, *OE* is output energy (MJ $ha^{-1}$), *IE* is input energy (MJ $ha^{-1}$), *NEG* is net energy gain (MJ $ha^{-1}$), *SE* is specific energy (MJ $kg^{-1}$), and *EP* is energy productivity (kg $MJ^{-1}$). In addition to the energy indices, contribution of each input, direct, indirect, renewable, and non-renewable energies from the total input energy were also determined.

## 2.4 Greenhouse gas (GHG) emissions

The GHG emissions arising from farm IE were estimated using the emission factors associated with each IE (Maraseni et al., 2010). Emission of three GHG including $CO_2$, $N_2O$, and $CH_4$ were estimated in this study and all emissions data were converted into carbon dioxide equivalent ($CO_2e$) to facilitate the comparison between GHG emissions from different farm practices (Maraseni et al., 2010). To convert $N_2O$ and $CH_4$ to $CO_2e$, factors of 298 and 25 were considered, respectively (Maraseni et al., 2010). GHG emission estimations included emissions due to the production and combustion of fossil fuels, emissions from the production, packaging, storage, and transportation of agrochemicals, emissions of $N_2O$ from soils due to N-fertilizer application, emissions due to the extraction, production, and use of electricity for crop irrigation, and emissions due to the production of farm machineries (Maraseni et al., 2010).

### 2.4.1 GHG emissions of fossil fuels

GHG are emitted from fossil fuels during production, combustion, and transportation of these fuels. Since GHG emissions during the transportation of fuels are negligible (Maraseni et al., 2007), only production and combustion portions were considered in this study. The value of 3.15 kg carbon dioxide equivalent was considered for the total GHG emissions during the production and combustion of 1 litre of diesel (Maraseni et al., 2010). Total diesel consumption for tillage and planting operations in corn production were measured in the field, while fuel consumption for spraying and harvesting operations were estimated using published data in literature (Kitani et al., 1999). Then the total fuel consumption was used to estimate the total values of GHG emissions resulting from farm diesel usage.

### 2.4.2 GHG emissions from agrochemicals

Production, packaging, storage, and transportation of agro-chemicals (fertilizers and herbicides in this study) require energy; thus, they contribute to GHG emissions. Three types of fertilizers including N, P, and K were used during corn growing season. Carbon dioxide equivalent emissions for the production, packaging, storage, and transportation of each kg of N, P, and K and herbicides were calculated using the equivalent carbon emission factors suggested by Lal (2004) and C to $CO_2$

conversion factor, 3.67, which is the ratio of molecular weight of $CO_2$ to atomic weight of C. An additional amount of $CO_2$ emission (1.47 $CO_2$ kg$^{-1}$) was also considered for formulation of herbicides as suggested by Lal (2004).

2.4.3 Emissions of $N_2O$ from soil due to N-fertilizer application

Nitrous oxide ($N_2O$) emission from soil related to N-fertilizer was calculated using the following equation (O'Halloran et al., 2008):

$$E_N = M \times EF \times C_g \qquad (7)$$

Where $E_N$ is the annual emissions from N-fertiliser (kg $N_2O$ ha$^{-1}$); $M$ is the mass of fertiliser applied to one hectare of farm (kg N ha$^{-1}$); $EF$ is the emission factor which is considered 0.021 (kg $N_2O$-N kg$^{-1}$ N applied) for irrigated crops as suggested by O'Halloran et al. (2008); and $C_g$ is a factor to convert elemental mass of $N_2O$ to molecular mass (44/28=1.57). Then, $N_2O$ emission was multiplied by the conversion factor of 298 to convert this emission into $CO_2$e.

2.4.4 GHG emissions due to use of electricity for crop irrigation

Water consumed for irrigating corn were measured using flow meter and electric energy required for pumping irrigation water was calculated using Equation 2. Emission factor of 251 kg $Co_2$e GJ$^{-1}$ was considered to convert the consumed electric energy to $Co_2$e emission (DEE, 2018). In addition to the $CO_2$e emitted due to electricity energy consumed for pumping irrigation water, emissions of 59.82, 311.6, and 34.5 kg $CO_2$e ha$^{-1}$ year$^{-1}$ (16.3, 84.9, and 9.4 kg CE ha$^{-1}$ year$^{-1}$) were considered for installation of hand moved SpI, DI, and SI, respectively as suggested by Lal (2004).

2.4.5 Emissions due to the production of farm machineries

Greenhouse gas emissions resulted from production of farm machineries were calculated using the following equation (Maraseni et al., 2007):

$$GHG_{fm} = W \times GHG_i \times F \qquad (8)$$

Where $GHG_{fm}$ is total GHG emissions due to production of farm machinery (kg $CO_2$e ha$^{-1}$), $W$ is weight of machine (*kg*), and $F$ is the portion of lifespan of the machine used for a given farm activities which is defined as $F = \frac{1}{L \times Ca_e}$ [$L$ is machine lifespan (*hr*) and $Ca_e$ is machine effective field capacity (*ha hr$^{-1}$*)]. Energy required to produce one kilogram of each farm machine used in wheat-corn cropping system was extracted from Kitani et al. (1999) in MJ kg$^{-1}$ and then converted to kWh kg$^{-1}$ (divided by 3.6). The resulted energy in kWh kg$^{-1}$ was multiplied by 0.411($CO_2$e GHGs emission for producing one kWh energy based on data provided by Maraseni et al. (2007)) to obtain the $CO_2$e GHGs emitted into the atmosphere while producing each kg of machinery ($GHG_i$ in Equation 8). Total GHG emissions were calculated as summation of emitted GHGs from different sources and GHG emissions intensity was obtained using the following equation:

$$GHGI = {}^{TGHG}/_{Y} \qquad (9)$$

Where $GHGI$ is greenhouse gas emission intensity (kg kg$^{-1}$), $TGHG$ is total GHG emission (kg $CO_2$e ha$^{-1}$), and $Y$ is crop dry matter yield (kg ha$^{-1}$).

### 2.5 Data analysis

Data were statistically analyzed using SAS software and Duncan's multiple range tests was used for means comparison.

## 3 Results and discussion

### 3.1 Energy use

Irrigation method had significant effect ($p<0.01$) on IE, OE, EUE, NEG, EP, and SE of corn production (Table 3). Significant effect of irrigation methods on IE, OE, IE, OE, EUE, NEG, and EP was due to different water use efficiencies of irrigation methods and consequently different amount of water supplied to the crop in different irrigation methods. IE, OE, and NEG were significantly affected by tillage method, but tillage method had no significant effect on EUE, EP, and SE (Table 3). Conservation tillage methods consumed less machinery and fuel energy compared to the CT; therefore, tillage effect on input energy was significant. Energy requirement reduction under conservation tillage compared to the CT has been also reported in literature (Chen and Baillie, 2009; Chen et al., 2015; Baillie, 2009). Also, corn yield significantly varied in various tillage methods; thus, OE and NEG were significantly different in various tillage methods.

**Table 3 Variance analysis of input and output energies, and energy indices data**

| Variation resources | df | IE | OE | EUE | NEG | EP | SE |
|---|---|---|---|---|---|---|---|
| Replication | 2 | $2.6\times10^{4ns}$ | $2.6\times10^{8\,ns}$ | $0.03^{ns}$ | $2.6\times10^{8\,ns}$ | $0.0001^{ns}$ | $1.76^{ns}$ |
| Irrigation | 2 | $1.4\times10^{10**}$ | $4.6\times10^{9**}$ | $2.58^{**}$ | $3.4\times10^{10\,**}$ | $0.0114^{**}$ | $511.6^{**}$ |
| Tillage | 2 | $2\times10^{7\,**}$ | $3.3\times10^{8\,*}$ | $0.04^{ns}$ | $5.1\times10^{8\,*}$ | $0.0002^{ns}$ | $10.8^{ns}$ |
| Irrigation × Tillage | 4 | $7.5\times10^{4*}$ | $7.5\times10^{8*}$ | $0.07^{*}$ | $7.3\times10^{8\,*}$ | $0.0003^{*}$ | $7.4^{*}$ |
| Error | 12 | $2.1\times10^{4}$ | $2.1\times10^{8}$ | 0.01 | $2.0\times10^{8}$ | 0.0001 | 4.8 |

Note: $^{ns}$: Non-significant; $^{*}$: significant at $p<0.05$; and $^{**}$: significant at $p<0.01$.

Corn production under SI consumed the highest input energy (165856 MJ $ha^{-1}$) followed by SpI (117662 MJ $ha^{-1}$) and DI (88597 MJ $ha^{-1}$), DI and SpI reduced IE by 45% and 29%, respectively compared to the SI (Table 4). The main reason for IE reduction in DI and SpI was higher irrigation efficiency and consequently lower water supplement to the field in these two irrigation methods compared to the SI. IE range of 30000 to 64000 MJ $ha^{-1}$ has been reported for different parts of world in the literature (Grassini and Cassman, 2012; Lorzadeh et al., 2012; Houshyar et al., 2012; Banaeian and Zangeneh, 2011) which is a wide range and far from what we have found in this study. IE for crop production is significantly affected by utilized inputs especially irrigation water parameters including irrigation system, source of irrigation water (rainfall, surface water, or groundwater) and the depth from which groundwater is pumped. Therefore, a big discrepancy is observed between reported values for IE of corn production in literature. Corn production under DI produced the highest OE (150552 MJ $ha^{-1}$) because of its higher crop yield. Corn production under SI not only consumed the highest energy but also produced the lowest OE (105324 MJ $ha^{-1}$); therefore, corn production under this irrigation method had the lowest EUE, NEG, and EP and the highest SE. Range of 103000 to 159000 MJ $ha^{-1}$ was found in literature for OE of corn grain production (Lorzadeh et al., 2012; Banaeian and Zangeneh, 2011; Grassini and Cassman, 2012) which covers the range of OE that was found in this study. Consumed energy in SI was higher than its produced energy; therefore, EUE in this irrigation practices was smaller than one and NEG was negative. The highest EUE, NEG, and EP and the lowest SE were recorded under DI because of its lower IE and higher OE. CT had the highest IE (125692 MJ $ha^{-1}$) and the lowest OE (120636 MJ $ha^{-1}$) followed by reduced (123557 and 128483 MJ $ha^{-1}$, respectively) and NT (122865 and 132499 MJ $ha^{-1}$, respectively) methods (Table 4). NT reduced corn EI and increased grain corn OE by 2.3% and 9.8%, respectively compared to the CT because of lower fuel and machinery energy requirement and higher crop yield. Therefore, conservation tillage methods (RT and NT) increased EUE, NEG, and EP of grain corn production compared to the CT due to their lower IE and higher OE. Chen and Baillie (2009) showed that the minimum tillage reduced the overall fuel used on the farm by 10% compared to the CT. Baillie (2009) also reported that the RT and NT operations could save energy by 12% and 24%, respectively compared to the CT in Australia. On the other hand, the lowest specific energy (14.66 MJ $kg^{-1}$) was related to the NT because of its lower IE and higher crop yield followed by RT (15.78 MJ $kg^{-1}$) and CT (16.85 MJ $kg^{-1}$). Results also showed that IE, OE, EUE, NEG, EP, and SE during grain corn production were significantly affected by interaction between tillage and irrigation methods so that the RT irrigated by DI had the lowest SE, and highest OE, EUE, NEG, and EP. RT irrigated with DI reduced corn production energy requirement by 47% and increased energy generation of corn production by 68% compared to the CT irrigated with SI. Therefore, replacing the treatment under CT irrigated by SI with RT irrigated by DI in corn production could significantly reduce the energy requirement and improve EUE, NEG, and EP.

**Table 4 Means comparison of input and output energies, and energy indices in different treatments**

| Irrigation Methods | IE (MJ $ha^{-1}$) | OE (MJ $ha^{-1}$) | EUE | NEG (MJ $ha^{-1}$) | EP (kg $MJ^{-1}$) | SE (MJ $kg^{-1}$) |
|---|---|---|---|---|---|---|
| Sprinkler | 117662b | 125742b | 1.07b | 8080b | 0.071b | 14.54b |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Drip | | 88597c | 150552a | 1.70a | 61955a | 0.113a | 8.91c |
| Surface | | 165856a | 105324c | 0.64c | -60532c | 0.042c | 23.84a |
| Tillage Methods | | - | - | - | - | - | - |
| Conventional | | 125692a | 120636c | 0.96a | -5056c | 0.071a | 16.85a |
| Reduced | | 123557b | 128483ab | 1.04a | 4926b | 0.078a | 15.78a |
| No-tillage | | 122865c | 132499a | 1.08a | 9633a | 0.079a | 14.66a |
| Irrigation × Tillage | | - | - | - | - | - | - |
| Sprinkler | Conventional | 119306b | 118210c | 0.99b | -1096d | 0.066b | 15.62b |
| Sprinkler | Reduced | 117019b | 110853cd | 0.95b | -6166d | 0.063b | 16.17b |
| Sprinkler | No-tillage | 116660b | 148163b | 1.27b | 31503c | 0.085b | 11.83bc |
| Drip | Conventional | 90262c | 145087b | 1.61a | 54825b | 0.107a | 9.34c |
| Drip | Reduced | 88256c | 165917a | 1.88a | 77660a | 0.125a | 8.02c |
| Drip | No-tillage | 87272c | 140653b | 1.61a | 53381b | 0.107a | 9.37c |
| Surface | Conventional | 167508a | 98611e | 0.59c | -68897e | 0.039c | 25.59a |
| Surface | Reduced | 165395a | 10868d | 0.66c | -56715e | 0.044c | 23.15a |
| Surface | No-tillage | 164664a | 10868d | 0.66c | -55983e | 0.044c | 22.78a |

Note: a, b, c: Averages with different letters in each column are statistically different at $p<0.05$.

Results of energy consumption of each input and its share from total IE during corn production under different tillage methods (Table 5) showed that diesel fuel energy decreased from 5287 MJ ha$^{-1}$ in CT to 2926 MJ ha$^{-1}$ in NT and energy consumed by machineries decreased from 15053 MJ ha$^{-1}$ in CT to 14314 MJ ha$^{-1}$ in the NT. In contrast, energy consumed by chemicals increased from 342 MJ ha$^{-1}$ in the CT to 513 MJ ha$^{-1}$ in the NT. Therefore, total IE slightly decreased in conservational tillage methods with respect to the CT. In all tillage methods, electricity for pumping irrigation water had the highest contribution (more than 55.35%) in total energy consumption followed by fertilizers (more than 15.84%). Wang et al. (2015) also found that optimizing N-fertilizer application rate and reducing electricity for pumping irrigation water were the two key measures to improve energy efficiency in corn production. More than 64.56% of total energy requirement during corn production was consumed for irrigation operation (irrigation water and electricity for pumping irrigation water) in all tillage methods showing that irrigation operation would be the most important target that energy saving strategies should be focused on. More than 68.5% and 90.5% of total IE of grain corn production were direct energy and non-renewable energies in all tillage methods.

**Table 5 Energy inputs under different tillage methods**

| Inputs | CT | | RT | | NT | |
|---|---|---|---|---|---|---|
| | Energy consumed (MJ ha$^{-1}$) | Share (%) | Energy consumed (MJ ha$^{-1}$) | Share (%) | Energy consumed (MJ ha$^{-1}$) | Share (%) |
| Fuel | 5287 | 4.21 | 3571 | 2.89 | 2926 | 2.38 |
| Electricity | 69569 | 55.35 | 69569 | 56.31 | 69569 | 56.62 |
| Irrigation water | 11574 | 9.21 | 11574 | 9.37 | 11574 | 9.42 |
| Machineries | 15053 | 11.98 | 14482 | 11.72 | 14314 | 11.65 |
| Fertilizers | 19913 | 15.84 | 19913 | 16.12 | 19913 | 16.21 |
| Chemicals | 342 | 0.27 | 428 | 0.35 | 513 | 0.42 |
| Seeds | 2500 | 1.99 | 2500 | 2.02 | 2500 | 2.03 |
| Labour | 112 | 0.09 | 106 | 0.09 | 104 | 0.08 |
| Transportation | 1343 | 1.07 | 1415 | 1.15 | 1453 | 1.18 |
| Total input | 125692 | 100.00 | 123557 | 100.00 | 122866 | 100.00 |
| Direct energy | 86542 | 68.85 | 84820 | 68.65 | 84173 | 68.51 |
| Indirect energy | 39150 | 31.15 | 38737 | 31.35 | 38693 | 31.49 |
| Renewable energy | 11686 | 9.30 | 11680 | 9.45 | 11678 | 9.50 |
| Non-renewable energy | 114006 | 90.70 | 111877 | 90.55 | 111188 | 90.50 |

Energy consumed by irrigation water and electricity for pumping irrigation water decreased from 16768 and 100792 MJ ha$^{-1}$ under SI to 7166 and 43072 MJ ha$^{-1}$ under DI, respectively which significantly decreased in the total energy requirement for corn production under DI compared to under SI (Table 6). The most important point which should be noted is even consumption of irrigation operation (water and electricity) in corn production under SI was greater than the total IE under DI and almost equal to the total IE under SpI. This highlighted the significant role of irrigation operation in the total energy requirement on corn production.

Therefore, the key measure to reduce energy consumption in corn production is using efficient irrigation systems.

**Table 6 Energy inputs under different irrigation methods**

| Inputs | Sprinkler |  | Drip |  | Surface |  |
|---|---|---|---|---|---|---|
|  | Energy consumed (MJ ha$^{-1}$) | Share (%) | Energy consumed (MJ ha$^{-1}$) | Share (%) | Energy consumed (MJ ha$^{-1}$) | Share (%) |
| Fuel | 3928 | 3.34 | 3928 | 4.43 | 3928 | 2.37 |
| Electricity | 64844 | 55.11 | 43072 | 48.62 | 100792 | 60.77 |
| Irrigation water | 10788 | 9.17 | 7166 | 8.09 | 16768 | 10.11 |
| Machineries | 13766 | 11.70 | 9847 | 11.11 | 20236 | 12.20 |
| Fertilizers | 19913 | 16.92 | 19913 | 22.48 | 19913 | 12.01 |
| Chemicals | 428 | 0.36 | 428 | 0.48 | 428 | 0.26 |
| Seeds | 2500 | 2.12 | 2500 | 2.82 | 2500 | 1.51 |
| Labour | 108 | 0.09 | 108 | 0.12 | 108 | 0.06 |
| Transportation | 1389 | 1.18 | 1637 | 1.85 | 1185 | 0.71 |
| Total input | 117662 | 100.00 | 88597 | 100.00 | 165856 | 100.00 |
| Direct energy | 79667 | 67.71 | 54273 | 61.26 | 121595 | 73.31 |
| Indirect energy | 37995 | 32.29 | 34324 | 38.74 | 44261 | 26.69 |
| Renewable energy | 10895 | 9.26 | 7273 | 8.21 | 16875 | 10.17 |
| Non-renewable energy | 106767 | 90.74 | 81324 | 91.79 | 148980 | 89.83 |

## 3.2 Greenhouse gas emissions

The maximum total GHG during the corn production process was emitted in SI (29376 kg $CO_2$e ha$^{-1}$) followed by SpI (20363 kg $CO_2$e ha$^{-1}$) and DI (15025 kg $CO_2$e ha$^{-1}$) (Table 7). DI and SpI reduced the total GHG emissions of corn production compared to the SI by 48.9% and 30.7%, respectively. Producing one-kilogram grain corn emitted 5.02 kg $CO_2$e to the atmosphere in SI, while only 1.81 kg $CO_2$e emitted to the atmosphere for production of one kilogram corn in DI. The reason for reduction total GHG emission and GHG intensity of corn production in DI with respect to the SI was lower water consumption and consequently lower electricity utilization for pumping irrigation water in DI compared to the SI. Therefore, using appropriate irrigation system in corn production process could significantly decrease the amount of GHG emitted to the atmosphere and reduce risk of global warming. RT and NT slightly decreased the total GHG emission and GHG emission intensity of grain corn production compared to the CT; however, these reductions were not statistically significant (Table 7). Results of previous researches also proved that tillage methods had small effect or no significant effect on GHG emissions (Maraseni and Cockfield, 2011; Krauss et al., 2017). Interaction effect of tillage and irrigation methods on the total GHG emission and GHG intensity showed that the RT irrigated with DI had the lowest GHG emission and GHG intensity in corn production. Therefore, using RT and NT specially RT with DI in corn production is the most environment friendly treatment and could significantly reduce the environmental pollutions.

**Table 7 Means comparison of total GHG emissions and GHG emission intensities in different treatments**

| Irrigation Methods |  | Total GHG emission (kg $CO_2$e ha$^{-1}$) | GHG emission intensity (kg $CO_2$e kg$^{-1}$dry grain) |
|---|---|---|---|
| Sprinkler |  | 20363 b | 2.99 b |
| Drip |  | 15025 c | 1.80 c |
| Surface |  | 29376 a | 5.03 a |
| Tillage Methods |  | - | - |
| Conventional |  | 21703 a | 3.47 a |
| Reduced |  | 21549 a | 3.28 a |
| No-tillage |  | 21512 a | 3.06 a |
| Irrigation × Tillage |  | - | - |
| Sprinkler | Conventional | 20478 b | 3.19 b |
| Sprinkler | Reduced | 20324 b | 3.34 b |
| Sprinkler | No-tillage | 20287 b | 2.45 b |
| Drip | Conventional | 15140 c | 1.87 c |
| Drip | Reduced | 14986 c | 1.62 c |
| Drip | No-tillage | 14949 c | 1.91 c |
| Surface | Conventional | 29491 a | 5.36 a |

| | | | |
|---|---|---|---|
| Surface | Reduced | 29338 a | 4.89 a |
| Surface | No-tillage | 29300 a | 4.83 a |

Note: a, b, c: Averages with different letters in each column are statistically different at $p<0.05$.

Electricity for pumping irrigation water had the highest share in the total GHG emission during corn production (more than 80%) followed by $N_2O$ emission from N-fertilizer and agrochemicals in all tillage methods (Table 8). Therefore, the main source of air pollution during corn production is irrigation operation and efforts should be made to reduce this pollution by using high efficiency irrigation methods. Share of fossil fuels and production of farm machineries from total GHG emission decreased from CT to NT because of lower fuel and machinery used in RT and NT, while share of agrichemicals increased from CT to NT due to higher herbicide utilization in RT and NT.

**Table 8 Share of inputs from the total GHG emissions under different tillage methods.**

| Emission sources | CT | | RT | | NT | |
|---|---|---|---|---|---|---|
| | GHG emission (kg $CO_2e$ $ha^{-1}$) | Share (%) | GHG emission (kg $CO_2e$ $ha^{-1}$) | Share (%) | GHG emission (kg $CO_2e$ $ha^{-1}$) | Share (%) |
| Fossil fuels | 348 | 1.61 | 235 | 1.09 | 193 | 0.90 |
| Agrochemicals | 1276 | 5.88 | 1301 | 6.04 | 1325 | 6.16 |
| $N_2O$ from N-fertilizer | 2260 | 10.41 | 2260 | 10.49 | 2260 | 10.50 |
| Electricity for pumping irrigation water | 17530 | 80.77 | 17530 | 81.35 | 17530 | 81.49 |
| Production of farm machineries | 289 | 1.33 | 224 | 1.04 | 205 | 0.95 |
| Total GHG emissions | 21703 | 100.00 | 21549 | 100.00 | 21512 | 100.00 |

GHG emission due to use of electricity for crop irrigation increased from 10966 kg $CO_2$e $ha^{-1}$ in DI to 25318 kg $CO_2$e $ha^{-1}$ in SI showing that DI reduced GHG emitted from use of electricity for crop irrigation by 56.7% compared to SI because of its higher water use efficiency and lower water consumption (Table 9). SpI also decreased GHG emission due to use of electricity for crop irrigation by 35.6% compared to the surface irrigation. GHG emission due to use of electricity for crop irrigation in SI was greater than total GHG emissions in DI and SpI. This showed that the total GHG emission during grain corn production could be significantly reduced by using more efficient irrigation systems as well as using clean energy sources (such as solar energy) for pumping irrigation water.

**Table 9 Share of inputs from the total GHG emissions under different irrigation methods.**

| Emission sources | Sprinkler | | Drip | | Surface | |
|---|---|---|---|---|---|---|
| | GHG emission (kg $CO_2e$ $ha^{-1}$) | Share (%) | GHG emission (kg $CO_2e$ $ha^{-1}$) | Share (%) | GHG emission (kg $CO_2e$ $ha^{-1}$) | Share (%) |
| Fossil fuels | 259 | 1.27 | 259 | 1.72 | 259 | 0.88 |
| Agrochemicals | 1301 | 6.39 | 1301 | 8.66 | 1301 | 4.43 |
| $N_2O$ from N-fertilizer | 2260 | 11.10 | 2260 | 15.04 | 2260 | 7.69 |
| Electricity for pumping irrigation water | 16305 | 80.07 | 10966 | 72.99 | 25318 | 86.18 |
| Production of farm machineries | 239 | 1.17 | 239 | 1.59 | 239 | 0.81 |
| Total GHG emissions | 20363 | 100.00 | 15025 | 100.00 | 29376 | 100.00 |

## 4 Conclusions

In this study, energy use and GHG emissions on corn production under different tillage and irrigation methods were evaluated. Based on the results, the following conclusions can be made:

Irrigation method has significant effect on energy use, energy production, energy use efficiency, net energy gain, specific energy, and energy productivity of corn production so that DI has the lowest energy use and specific energy, and the highest output energy, energy use efficiency, net energy gain, and energy productivity followed by sprinkler and surface irrigations. Replacing SI with DI on corn production would reduce IE by 45%, increase OE by 43.5%, and inprove energy use efficiency, net energy gain, and energy productivity.

Tillage methods have aslo significant effect on IE, OE, and NEG of grain corn production in such a way that RT and NT reduces energy requirment, and increases OE and NEG. For this reason, corn production under RT irrigated with DI would reduce IE by 47% and increase OE by 68% compared to the CT irrigated with SI. Therefore, treatment containing RT and DI is the most energy efficient treatment on corn production.

Irrigation method has significant effect on the total GHG emission and GHG emission intensity on corn production so that DI reduces GHG emission by 48.9% and GHG emission intensity by 64% compared to the SI. Tillage method has no significant effect on total GHG emission and GHG emission intensity of corn production.

Since treatment containing RT and DI on corn production has the lowest IE, SE, total GHG emission, and GHG emission intensity and highest OE, EUE, NEG, and EP, this treatment is the most energy efficient and evironment friendly treatment of corn production.

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