Gorgan University of Agricultural Sciences and Natural Resources

Environmental Resources Research (ERR)

Print ISSN: 2783-4832
Online ISSN: 2783-4670

Comparative analysis for energy technique and life cycle assessment approach of triticale production with phosphorus solubilizing bacteria

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Article Info

Article type:
Research Article

Article history:
Received: September 2022
Accepted: May 2023

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Keywords:
Energy
Life cycle assessment
Sustainable agriculture
Phosphorus solubilizing bacteria

Abstract

The present article focuses on the utilization of phosphorus-solubilizing bacteria to enhance sustainable triticale wheat farming. Energy and environmental indicators were significantly influenced by the management method of triticale production. The operational plots in the Agricultural Institute of Golestan Province, Iran, consisted of (A1) the plot without the use of basic fertilizer but with the application of phosphate-solubilizing bacteria, and (A2) the plot using triple superphosphate fertilizer at a rate of 50 kg per hectare. Analysis of energy consumption revealed significant differences. Energy ratio, energy productivity, energy intensity, and net energy gain were calculated using standard equations. The lower input energy (7586.11 MJ ha–1) and the higher output energy (10265.06 MJ ha–1) of A1 indicated an advantageous energy ratio of A1 (1.35). Environmental impact management in the agricultural sector is a crucial factor for the food production chain. A life cycle assessment of triticale was conducted using the ReCiPe2016 method. The environmental emissions of A1 in the categories of damage to human health, ecosystem quality, and resources were lower than those of A2. Diesel fuel and chemical fertilizer consumption are influenced by cultivation conditions and the application of phosphorus-solubilizing bacteria. The adverse effects of inputs under A1 conditions on energy consumption and environmental emissions are less pronounced.

Cite this article: Taherzadeh-Shalmaei, Nahid; Sharifi, Mohammad; Armashi, Rahmatollah; Mobli, Hossein. 2023. Comparative analysis for energy technique and life cycle assessment approach of triticale production with phosphorus solubilizing bacteria. *Environmental Resources Research*, 11(2), 209-224.

DOI: 10.22069/ijerr.2024.21645.1411
Publisher: Gorgan University of Agricultural Sciences and Natural Resources

Introduction

Due to increasing population growth, food supply has become a primary national strategy in various countries (Balda and Kawajiri, 2020). Based on the statistics six times production with 80 times energy consumption reflects high energy usage in the field (Kaur et al., 2021). Energy efficiency in modern systems has decreased compared to traditional methods, posing a challenge to the sustainability of current agricultural practices (Bhunia et al., 2021). Agriculture and the production of agricultural products constitute a major activity in many rural communities in Iran, with most energy consumption occurring within the agricultural systems (Nabavi-Pelesaraei et al., 2019). Analyzing the energy consumption pattern and efficiency in agricultural systems by identifying where energy is wasted is crucial for decision-making and planning in the management and development of the agricultural sector (Rathke and Diepenbrock, 2006). Energy in agricultural systems can be categorized into input energies, such as solar energy and agricultural energy, and output energies (AghaAlikhani et al., 2013).

The cultivation of triticale as the first man-made product aimed to combine the quality characteristics of wheat and the ability to tolerate environmental stresses in new crops. Triticale demonstrates a high capacity to withstand environmental stresses (Santiver et al., 2004). In Iran, the prevalence of infertile lands is increasing, and drought remains a primary limiting factor in wheat fields. Therefore, altering planting patterns and introducing crops that can endure harsh conditions becomes necessary (Martinek et al., 2008). Numerous studies attribute triticale to its response to drought stress, emphasizing its superior water absorption capability compared to wheat (Jørgensen et al., 2007). While primarily grown as a forage crop, triticale is a rich source of protein and amino acids, playing a crucial role in both direct livestock feeding and indirect human food (Santiver et al., 2004).

The energy efficiency of an agricultural production system is determined by the energy equivalent of the yield produced and the energy equivalent of all agricultural inputs and operations. To enhance efficiency, inputs must be minimized, and crop yields increased (Yuan and Peng, 2017b). Wheat production exhibits different responses to nitrogen use efficiency, influenced by variations in growing season conditions and soil properties. However, an increase in nitrogen consumption often results in decreased nitrogen use efficiency in wheat production (Muurinen et al., 2006). The effective use of energy in agriculture is a crucial condition for sustainable agriculture, optimizing consumption, preserving fossil fuels, and reducing air pollution (Bhunia et al., 2021).

Research by Sharma et al. (2011) on the frequency of wheat-corn planting revealed that the energy requirements for minimum tillage, no tillage, and ridge cultivation were 34.3%, 31.1%, and 46% less than conventional tillage, respectively. The tillage system stored at least 2.5 times more energy than a conventional tillage system. Experimental results on the effect of tillage on wheat yield showed that the average yield of wheat in chisel plow and moldboard plow treatments was higher than other treatments. Chisel plow emerges as a suitable alternative to moldboard plow due to lower energy consumption and increased speed of tillage operations (Moitzi et al., 2013). In a study by KOŠUTIĆ et al. (2005) investigating different tillage methods on energy consumption, conventional tillage had the highest energy consumption (1813 MJ/ha). Energy savings in conservation and non-plowing methods were 37.5% and 85%, respectively, with an average fuel consumption of 61 liters per ha reported for conventional tillage. Agricultural operations relying on the combustion of fossil fuels have a significant impact on global carbon and the nitrogen cycle. Farmers can mitigate greenhouse gas emissions through proper management practices (Rattanatum et al., 2018). This reduction is achieved by minimizing the ecological footprint of agricultural products on the farm (IPCC, 2006). Improving crop practices plays a crucial role in reducing a substantial portion of greenhouse gas emissions. Life cycle assessment (LCA) is a suitable method for studying the environmental effects of a product throughout its life cycle within the system (Frischknecht et al., 2015). Investigation of environmental effects, as indicated by ecological index values under nitrogen consumption conditions of less than 150 kg/ha, ranged from 0.22 to 0.26 per ton of wheat. An increase in nitrogen application from 200 to 390 kg/ha resulted in an increase in the ecological index of the crop (Brentrup et al., 2004). Wowra et al. (2021) assessed the life cycle impact of nitrogen consumption on wheat production systems, comparing compact and non-compact crop systems in Switzerland using the LCA method (Nemecek et al., 2011). Data for this research were collected from various ongoing experiments. Similar studies employing a comparable pattern examined environmental impacts from crop production based on data from questionnaires or official databases (Araujo et al., 2020; Taherzadeh-Shalmaei et al., 2021).

Importance of Phosphorus Solubilizing Bacteria (PSB)

Phosphorus, as an essential component of energy metabolism, plays a crucial role in the production and transmission of plant energy. Root growth, stem strength, flower and seed formation, nitrogen fixation in legume plants, crop quality, and disease resistance are directly influenced by phosphorus consumption (Haefner et al., 2005). The addition of large amounts of phosphorus fertilizer to the soil can lead to sedimentation and make it inaccessible to plants. Many studies are exploring suitable alternatives to phosphate fertilizers to minimize environmental and human health hazards (Khan et al., 2009). Renewable inputs contribute to maintaining a sustainable agricultural system with maximum environmental benefits and minimal environmental damage (Naiman et al., 2009). Various types of microorganisms are commonly employed in agricultural activities. Microorganisms have the ability to form colonies in the root environment and communicate with plants, influencing biomass growth, root development, and economic performance. These organisms are known as plant growth-promoting rhizobacteria (PGPR). Bacteria accelerate growth and increase yields by affecting the mechanisms of plant root action and influencing plant physiology (Sturz and Christie, 2003; Van loon, 2007). Fertilizers are currently used to achieve maximum production per unit area; however, the use of chemical fertilizers can lead to imbalances. Under unfavorable conditions, this not only results in increased yields but also contributes to the waste of agricultural capital and environmental problems. Bio-fertilizers enhance plant growth in agricultural production by increasing bacterial activity (Smith and Zhu, 2001). Phosphate-solubilizing microorganisms are beneficial in providing plant-absorbable forms and reducing environmental pollution. Therefore, understanding the status of phosphorus and its forms in calcareous soils of Iran holds special importance. The aim of this study was to investigate the role of phosphate solubilizing bacteria on usable amounts of phosphorus and its effect on energy and environmental emissions. Also, the variables involved in energy efficiency and its improvement were identified to analyze various issues in sustainable agricultural systems, conservation of environmental resources and prevention of environmental degradation. Careful examination of all sources of greenhouse gas emissions and the amount of pollution in each section was conducted. As a result, appropriate solutions are proposed to change the relevant production method.

Materials and methods

Field Experiment

The information required for the research was collected from the Agricultural Institute of Golestan Province, Iran. Table 1 shows the soil physicochemical properties. The operating plots in this study included the plot without the use of basic fertilizer but with application of phosphate solubilizing bacteria (PSB) in soil (A_1) and the plot with the use of triple superphosphate fertilizer at a rate of 50 kg ha^{-1} (A_2). The final consumption of inputs was determined based on the average consumption of agricultural inputs. Subsequently, the amount of energy consumption, energy indicators, and environmental emissions in various tillage systems were computed.

Table 1. Physicochemical parameters of soil collected from the study area.

Properties	Result
Depth (cm)	0-30
EC (ds m^{-1})	1.2
pH	7.8
O.C (%)	1.7
N (%)	0.18
P (mg kg^{-1})	43
K (mg kg^{-1})	520
Clay (%)	30
Lom (%)	42
Sand (%)	28
Soil texture	C-L

EC: Electrical conductivity, O.C: Organic carbon, P: Phosphorus, K: Potassium, C-L: Clay-Loam.

Energy usage in Triticale Production

Agriculture represents an energy conversion process where solar energy, soil nutrient energy, and supporting energies, such as fossil fuel products, are transformed into essential resources like food, straw, and fiber for human and animal consumption (Yuan and Peng, 2017a). Examining and calculating input and output flows in production systems is integral to sustainable development, with energy analysis providing insights into system strengths and weaknesses (Soni et al., 2018). Inputs such as fuel, electricity, machinery, seeds, chemical fertilizers, and pesticides play a significant role in the energy supply of agricultural products (He et al., 2017). The diversity of inputs has led to substantial changes in the energy consumption pattern of the agricultural sector, making various productions more reliant on fossil fuel energy sources (Brentrup and Pallière, 2008). Table 2 illustrates the designated inputs in triticale production and their corresponding energy equivalents. The sustainability of production, system energy optimization, preservation of fossil fuel reserves, and the reduction of effective air pollution hinge on comprehensive energy analysis (Dalgaard et al., 2001). Consequently, a fundamental analysis of energy and its resources is essential. Implementing specific policies addressing food needs, waste reduction, and the utilization of new resources contributes to proper energy use and encourages consumer conservation efforts (Khan et al., 2010).

Table 2. Energy coefficients and energy inputs-output in triticale production.

Items	Unit	Energy equivalent (MJ $unit^{-1}$)	References
A. Inputs			
1. Human labor (h)	h	1.96	(Nabavi-pelesaraei et al., 2014)
2. Operation time (h)	h	64.80	(Singh, 2002)
3. Diesel fuel (L)	L	56.31	(Rafiee et al., 2010)
4. Nitrogen (kg)	kg	12.44	(AghaAlikhani et al., 2013)
5. Phosphate (kg)	kg	66.14	(AghaAlikhani et al., 2013)
6. Herbicide (kg)	kg	190.00	(Badger, 1999)
7. Fungicides (kg)	kg	61.00	(Badger, 1999)
8. Seed (kg)	kg	9	(Bielski et al., 2015)
B. Outputs			
1. Triticale	kg	18.35	(Bielski et al., 2015)
2. Straw	kg	16.47	(Badger, 1999)

[a] The economic life of machine (year).

Energy balance in agriculture is obtained by comparing the input and output energies in an agricultural system. The product of the energy equivalent (energy of each unit of inputs) multiplied by the amount of inputs used shows the amount of the energy entering the farm. The output energy is calculated in the same manner (Yang et al., 2022). Energy indices for different crops in crop systems are compared and evaluated in terms of energy ratio, energy productivity, energy intensity and net energy gain (Kazemi et al., 2015). These indicators are as follows (Mohammadi et al., 2010):

1. Energy ratio (ER) is the most important indicator in evaluating the energy of agricultural systems. The relationship between the output energy (E_{out}) and the input energy (E_{in}) is expressed as Equation (1). Output and input energy are calculated in MJ. As a result, this index does not have a unit. The difference between the energy of the outputs and the energy of the inputs shows the net energy gain (NEG) index. NEG is calculated by Equation 2.

$$\mathrm{ER} = \frac{E_{out}}{E_{in}} \quad (1)$$

$$\mathrm{NEG} = E_{out} - E_{in} \quad (2)$$

2. The amount of triticale production (Y) per unit of energy consumption (E_{in}) is called energy productivity (EP). The unit of EP index is kg per MJ (Equation 3). Optimal energy consumption of inputs and increase of yield are effective in better estimation of results.

$$\mathrm{EP} = \frac{Y}{E_{in}} \quad (3)$$

3. Energy intensity (EI) is the opposite of EP. EI indicates the amount of energy consumed (E_{in}) per unit of product production (Y). The optimal degree of energy use is calculated by Equation 4.

$$EI = \frac{E_{in}}{Y} \quad (4)$$

LCA method

One of the primary contributors to environmental problems is the reliance of conventional farming systems on high energy usage. This discussion delves into comprehensive calculations assessing the sustainability of agricultural systems and the sectors that contribute to increased environmental pollution (Qiao et al., 2014). In this context, life cycle assessment (LCA) emerges as a valuable tool for studying and determining the environmental impact of agricultural products. In many countries, LCA is regarded as a decision-making tool in agricultural production (Niero et al., 2015). LCA is an appropriate method for evaluating environmental and resource impacts throughout a product's life cycle, taking into account various dimensions of the environment, human health, and resources (Saber et al., 2020). The different stages of LCA are detailed in Table 3. The resource life cycle encompasses every step from raw material production, extraction, processing, transportation, production, storage, and distribution. Each stage has varying effects on different environmental, economic, and social dimensions (Dijkman et al., 2018).

The aim of life cycle assessment is to analyze environmental emissions to identify the hotspots in the triticale production life cycle. The functional unit serves as a reference by which the yield of the systems under study is measured, with one ton of triticale product as the functional unit in this research. Figure 1 delineates the system boundaries for evaluating the life cycle of triticale production. The life cycle assessment in this study involves gathering information necessary to quantify all inputs and outputs associated with the production of one ton of triticale. On-farm emissions from diesel fuel, chemical fertilizer elements, and heavy metals are categorized as Sm1, 2, and 3, respectively (see supplementary material). Understanding the origin of environmental effects or identifying milestones for improving environmental performance and decision-making influences their outcomes. The determined coefficients are extracted from the Ecoinvent base and impact the environmental emissions of triticale production (Houshyar et al., 2017). Environmental emissions to air, water, and soil are categorized in the following tables. The obtained information was analyzed using SimaPro software and the ReCiPe2016 method. This practical method presents the implementation of ISO standards in the form of a project. The life cycle assessment step is introduced using classification methods and special effects features along with inventory executable files (ISO, 2006). The use of impact assessment factors in basic data is simple and prevents potential errors during conversion. The results are classified using different effects based on their impact (Dijkman et al., 2018). The results and discussions related to the analysis should align with the purpose and scope of the study. Checking for completeness of information regarding overlooked points is a way to avoid mistakes in conducting life cycle assessments. The final stage report aids in making informed decisions and policies, providing swift and acceptable results for multiple decisions (Wowra et al., 2021).

Table 3. Overview of the steps of the LCA method.

Phase	Method	The main result	Reference
1. Define Goal and Scope	(a). Definition of goal (b). Definition of scope (c). Functional unit (d). Resource replacement (e). Resource flow	✓ Analyze results with functional units ✓ Compare alternatives	Habibi et al. (2019)
2. Life Cycle Inventory (LCI)	(a). Boundary of environmental systems (b). Flow Chart (c). Categorize templates and data (d). Data collection and communication (e). Data validation (f). Estimating data (g). Assignment of calculation method	✓ Inventory tables ✓ System boundary shape	Yadav and Mishra. (2013)
3. Life Cycle Impact Assessment (LCIA)	(a). Select the calculation method (b). Select index, characterization model, standardization (c). Normalization (d). Weighing	✓ Evaluate impact categories	Wang et al. (2010)
4. Interpretation of Results	(a). Compatibility check (b). Check for completeness (c). Share the analysis (d). Sensitivity analysis	✓ Balanced conclusions ✓ Recommendations	Noya et al. (2015)

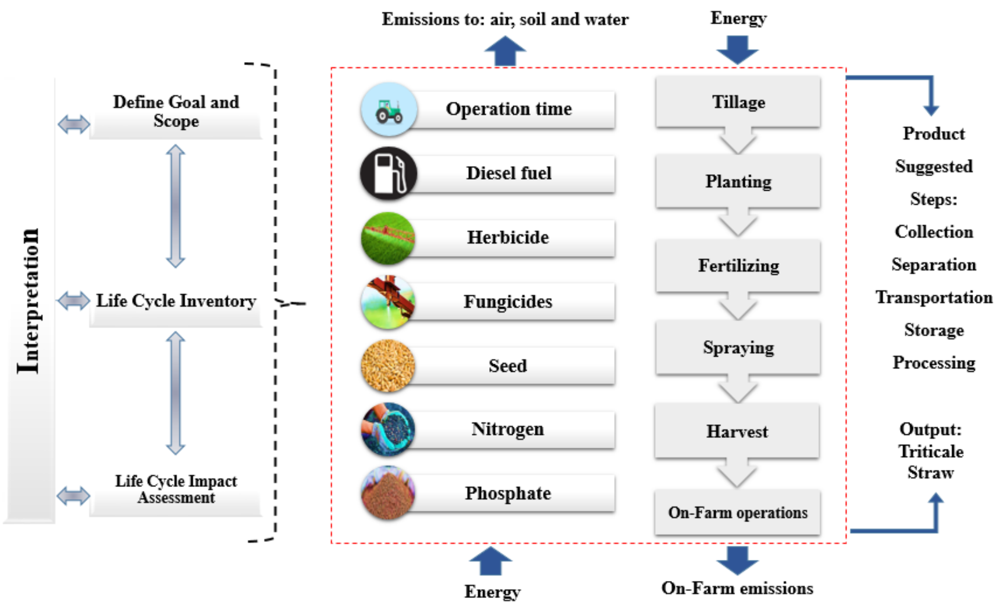


Figure 1. System boundary of different stages of triticale production

Results and discussion

Energy analysis in different stages

Energy consumption in different triticale cultivation periods was estimated and the results are presented in Table 4 (A_1) and Table 5 (A_2) for better comparison. The input energy in the plot without phosphorus solubilizing bacteria (A_2) was significant. Energy consumption at the fertilizing stage is 4275.06 MJ ha^{-1}. As a result, more energy is consumed at this stage than at other stages. The planting (2631.94 MJ ha^{-1}) and tillage (1032.65 MJ ha^{-1}) stages fall in the second and third ranks in terms of energy consumption compared to all stages. The energy of the spraying stage is 580.76 MJ ha^{-1} due to lower fuel consumption and optimal use of herbicides and fungicides. The total energy input in the plot with phosphorus-solubilizing bacteria (A1) is 7586.11 MJ/ha–1, while in the plot without phosphorus-solubilizing bacteria (A2), it is 9209.37 MJ/ha–1. Consequently, the new approach can result in reduced energy consumption. In the case of paddy rice production in the Philippines, the average total energy input ranges from 12.4 to 13.1 GJ/ha (Quilty et al., 2014). Sweet sorghum production, classified into low-input technology and high-input technology, shows maximum energy consumption of 15.8 GJ/ha and 226 GJ/ha, respectively (Jankowski et al., 2020). Another study estimates the average total energy consumption for wheat production at 30,000 MJ/ha, with reduced tillage systems exhibiting the lowest input energy (Houshyar and Grundmann, 2017). Energy consumption analysis in wheat production in West Azarbaijan, Iran, reveals an input energy of 30626.4 MJ/ha (Taghavifar and Mardani, 2015), a significant amount compared to triticale cultivation.

Figure 2 illustrates the contribution of energy inputs to triticale production. In the plot with phosphorus-solubilizing bacteria (A1), human labor energy decreases due to the non-use of phosphate fertilizer, leading to changes in the harvest phase for improved performance.

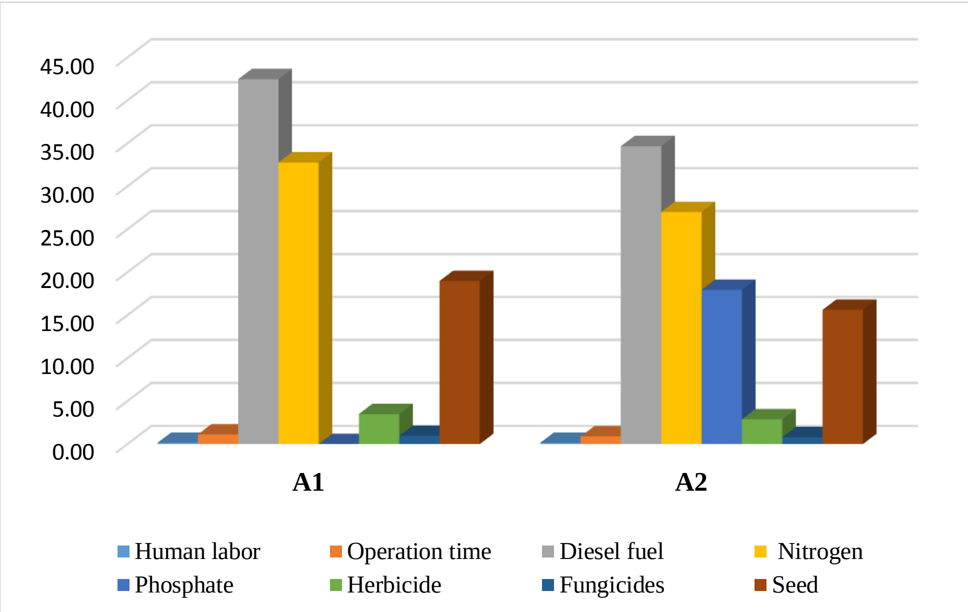


Figure 2. The share of energy consumed by the inputs.

Table 4. Energy inputs at different stages of triticale production (A_1).

Items	Tillage		Planting		Fertilizing		Spraying		Harvest		Total energy of inputs (MJ)
	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	
1. Human labor (h)	0.89	1.74	0.64	1.25	3.98	7.80	0.28	0.55	0.32	0.62	11.96
2. Operation time (h)	0.78	50.54	0.30	19.44	-	-	-	-	0.23	14.90	84.88
3. Diesel fuel (L)	17.41	980.36	20.80	1171.25	2.2	123.88	4.28	241.01	12.53	705.56	3222.06
4. Nitrogen (kg)	-	-	-	-	200.00	2488.00	-	-			2488.00
5. Phosphate (kg)	-	-	-	-	-	-	-	-	-	-	-
6. Herbicide (kg)	-	-	-	-	-	-	1.40	266.00	-	-	266.00
7. Fungicides (kg)	-	-	-	-	-	-	1.20	73.20	-	-	73.20
8. Seed (kg)	-	-	160	1440.00	-	-	-	-	-	-	1440.00
Total energy use(MJ)	-	**1032.65**	-	**2631.94**		**2619.68**		**580.76**		**721.08**	**7586.11**

Table 5. Energy inputs at different stages of triticale production (A_2).

Items	Tillage		Planting		Fertilizing		Spraying		Harvest		Total energy of inputs (MJ)
	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	Unit per ha	Energy (MJ ha^{-1})	
1. Human labor (h)	0.89	1.74	0.64	1.25	4.94	9.68	0.28	0.55	0.23	0.45	13.68
2. Operation time (h)	0.78	50.54	0.30	19.44	-	-	-	-	0.18	11.66	81.65
3. Diesel fuel (L)	17.41	980.36	20.80	1171.25	2.2	123.88	4.28	241.01	12.02	676.85	3193.34
4. Nitrogen (kg)	-	-	-	-	200.00	2488.00	-	-			2488.00
5. Phosphate (kg)	-	-	-	-	25.00	1653.50	-	-	-	-	1653.50
6. Herbicide (kg)	-	-	-	-	-	-	1.40	266.00	-	-	266.00
7. Fungicides (kg)	-	-	-	-	-	-	1.20	73.20	-	-	73.20
8. Seed (kg)	-	-	160	1440.00	-	-	-	-	-	-	1440.00
Total energy use (MJ)	-	**1032.65**	-	**2631.94**		**4275.06**		**580.76**		**688.96**	**9209.37**

Consequently, fuel consumption increases by over 40% due to extended operation time in the plot with phosphorus-solubilizing bacteria. Diesel fuel consumption for agricultural operations with machinery constitutes a significant share, accounting for 35% in the plot without phosphorus-solubilizing bacteria (A2). The consumption of chemical fertilizers, such as nitrogen (27%) and phosphate (18%), is also noteworthy. In rice production, energy consumption from nitrogen fertilizer and fossil fuel comprises over 60% of the total energy input (Quilty et al., 2014). Another study explores the increasing share of agricultural resources related to fossil energy. Reports indicate that pollution from chemical fertilizers has the most significant impact on the atmosphere (Zhang et al., 2015). Chemical fertilizer contributes to the highest energy consumption in semi-mechanized tillage (44%) and mechanized tillage (38%) in rice production. Diesel, irrigation water, seeds, and electricity are other energy-intensive inputs (Kumar et al., 2021). In a separate study, balancing nitrogen fertilizer with actual crop needs and adopting minimum tillage emerged as the most efficient techniques to reduce energy input (Alluvione et al., 2011). The seed used for growing triticale (15%) also holds a substantial share in the total energy input, primarily due to extensive agricultural machinery use in this study, minimizing the need for human labor.

Output energy and energy indicators are presented in Table 6. The output energy for the plot with phosphorus-solubilizing bacteria (A1) is 10,265.06 MJ/ha–1, while for the plot without phosphorus-solubilizing bacteria (A2), it is 9,761.58 MJ/ha–1. Consequently, the energy produced in the phosphorus-activating bacteria plot is significant, and the product performance has increased with the proposed method. In a study by Taghavifar and Mardani (2015), the output energy for wheat in Iran's cultivation conditions is reported as 53,480.4 MJ/ha–1, a considerably lower figure compared to the energy output of triticale. The Energy Ratio (ER) for the plot with phosphorus-solubilizing bacteria (A1) and without phosphorus-solubilizing bacteria (A2) is 1.35 and 1.06, respectively. Consequently, in terms of energy balance, the energy produced exceeds the energy consumed. Energy Productivity (EP) and Energy Intensity (EI) for A2 are 0.09 kg MJ−1 and 11.11 MJ kg−1, respectively. These indicators indicate that less energy was consumed than the product yield. In comparison, the energy efficiency of corn, wheat, and soybeans is reported as 2.2, 2.6, and 4.1 MJ kg−1 grain, respectively. This research considers crop rotation and crop management as crucial factors in determining the cropping system (Alluvione et al., 2011).

Table 6. Output energy and indicators of triticale production.

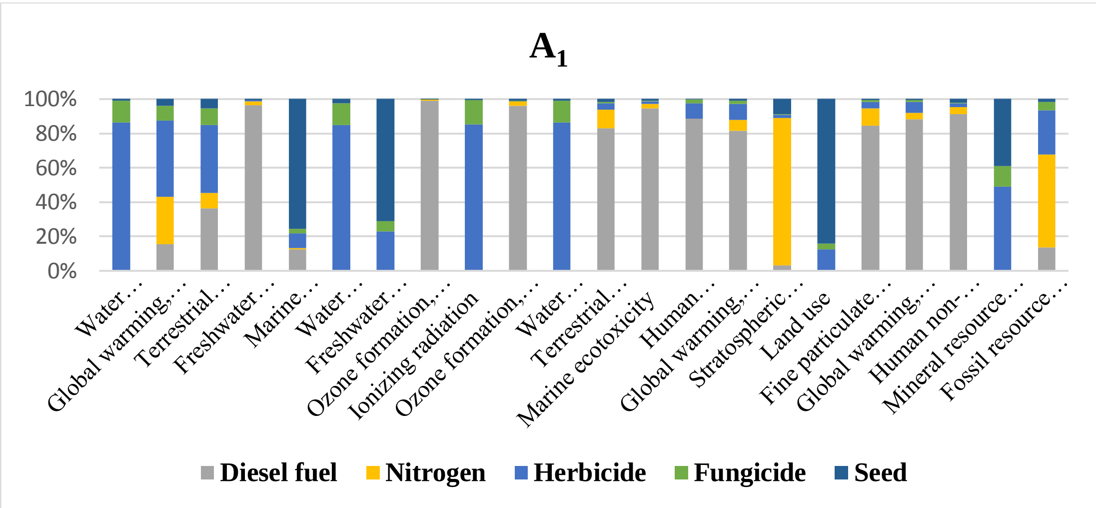
Items	Unit	Value (A_1)	Value (A_2)
A. Output			
1. Triticale	MJ ha^{-1}	7602.54	7164.76
2. Straw	MJ ha^{-1}	2662.52	2596.82
Total energy of outputs (MJ)	**-**	**10265.06**	**9761.58**
B. Indicators			
1. Energy ratio (ER)	-	1.35	1.06
2. Energy productivity (EP)	kg MJ^{-1}	0.09	0.06
3. Energy intensity (EI)	MJ kg^{-1}	11.11	16.80
4. Net energy gain (NEG)	MJ ha^{-1}	2678.95	552.21

In the study of Tahir et al., (2018), the combined application of bio-organic phosphate and phosphorous solubilizing bacteria significantly improved the growth, yield and productivity of two types of wheat compared to the control treatments. It increased the grain yield of Galaxy-2013 variety up to 54.3% and Punjab-2011 variety up to 83.3%. NEG has a positive value due to the energy balance. The NEG results for A_1 (2678.95 MJ ha^{-1}) showed that it produced more energy than A_2. Finally, the identification of agriculturally beneficial bacteria, especially phosphorus-solubilizing bacteria (PSB), that increase the efficient use of phosphorus, will support more sustainable cropping systems (Lynch and Brown, 2012).

Hotspot analysis of LCA

Table 7 shows the environmental emissions from one ton of triticale cultivation. Most categories of environmental emissions with phosphorus solubilizing bacteria have lower values than triticale cultivation without phosphorus-solubilizing bacteria. The category of human carcinogenic toxicity damage with 780 DALY plays an important role in the end points of damage for the plots without phosphorous solubilizing bacteria (A_2). Marine ecotoxicity and mineral resource scarcity damage categories, with 3.42 species·yr and 0.202 USD2013, respectively, exert the greatest impact on ecosystem and resource environmental emissions. Across all impact categories of wheat production, organic agriculture demonstrated lower environmental impacts, while conventional agriculture had a lesser impact on land use. The study considered acidification, photo-oxidant formation, ozone layer depletion, and non-renewable energy resource consumption for two similar cultivation systems (Verdi et al., 2022).

Similarly, research on wheat production indicated higher environmental emissions for rainfed wheat compared to irrigated wheat due to lower yield per hectare. The Abiotic Depletion (AD) and Acidification (AC) impact rates were 0.002–0.003 kg Sb eq and 8.991–11.863 kg SO2 eq for wheat production (irrigated and rainfed), respectively (Taki et al., 2018). Figure 3 illustrates the contribution of each input to the environmental emissions of damage categories. Diesel fuel consumption played a prominent role in environmental emissions across most damage categories. In the conditions of triticale cultivation with phosphorus-solubilizing bacteria, diesel fuel accounted for over 95% of environmental emissions in categories such as ozone formation (terrestrial ecosystem), ozone formation (human health), freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity. In triticale cultivation without phosphorus-solubilizing bacteria, environmental emissions from human non-carcinogenic toxicity constituted over 65% of fuel consumption.



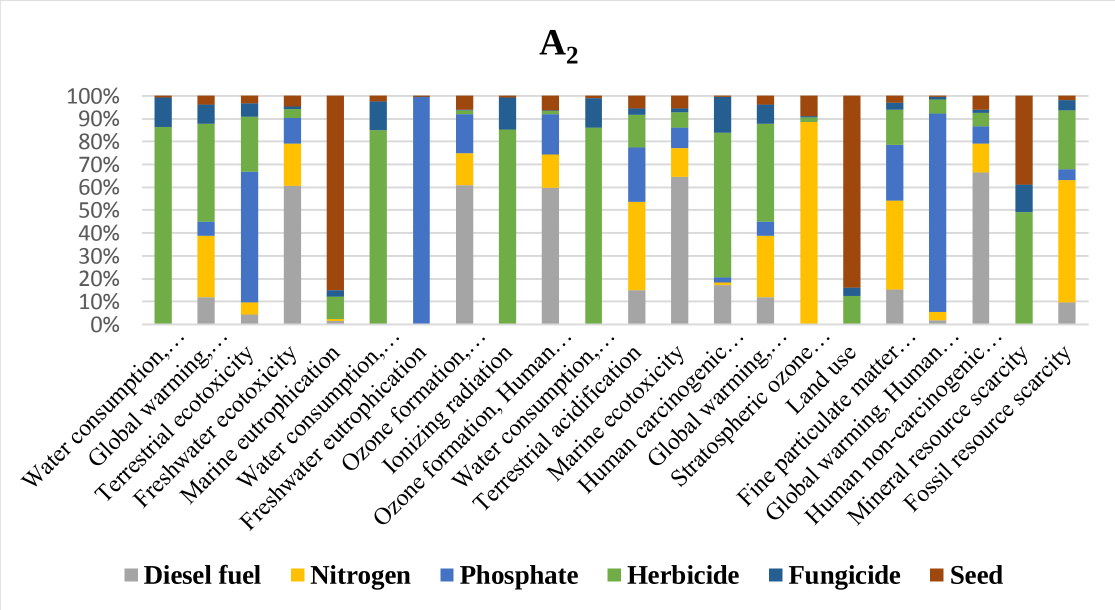


Figure 3. The share of mid-point impact categories by each of the inputs.

Concerning the critical issue of global warming and human health, the use of nitrogen fertilizers contributed to an increase in the average temperature of the Earth and ocean surfaces. The excessive use of herbicides during the spraying phase contributed to more than 85% of water consumption and aquatic ecosystem environmental emissions. In a dual production system, nitrogen and phosphorus fertilizer consumption in winter wheat production decreased by 23.5% and 79.7%, respectively. The reduced use of chemical fertilizers in the winter wheat-summer maize production system resulted in decreased global warming, acidification, and eutrophication potentials in water (Wang et al., 2014).

The results of the three endpoints of environmental emissions are shown in Table 8. The final environmental releases presented positive results in terms of the use of phosphorus solubilizing bacteria. The results for ecosystems, human health, and resources for the plots without phosphorus-solubilizing bacteria (A2) are 3.48 species·yr, 2.72 DALY, and 2.77 USD2013, respectively. When considering nitrogen application rates of 48, 96, 144, or 192 kg per hectare, the environmental index for the ecosystem exhibited values ranging from 0.16 to 0.22 per ton of grain in wheat production. At very low and high nitrogen rates, land use index and eutrophication had the highest environmental emissions, respectively (Brentrup et al., 2004). Figure 4 illustrates the environmental emissions resulting from input consumption. More than 50% of resource-related environmental emissions are attributed to the use of diesel fuel in the plot without phosphorus-solubilizing bacteria (A2). Diesel fuel consumption in the plot with phosphorus-solubilizing bacteria (A1) has a more substantial impact (86%) on human health. Nitrogen fertilizer negatively affects triticale cultivation conditions without phosphorus solubilizing bacteria, with 29%, 22%, and 23% contributing to damage in resources, human health, and ecosystems, respectively. In another study, the use of manure compost as an alternative to chemical fertilizers was recognized as an effective strategy for reducing environmental emissions in mid-point impact categories and all assessed damage categories (except human health and resources) (Jiang et al., 2021).

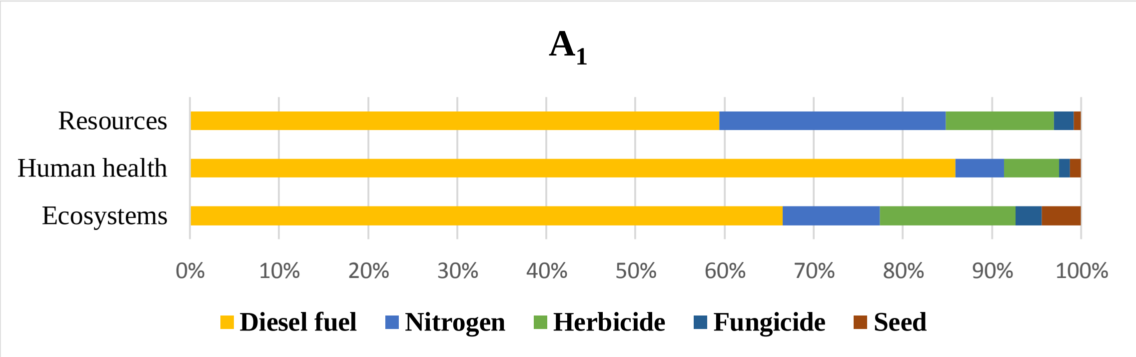
Table 7. The results of mid-point impact categories for producing one ton of triticale production.

Impact category	Units	Value (A_1)	Value (A_2)
Water consumption, Aquatic ecosystem	species.yr	2.75E-11	3.05E-11
Global warming, Freshwater ecosystem	species.yr	6.47E-09	6.86E-09
Terrestrial ecotoxicity	species.yr	2.93E-08	5.03E-08
Freshwater ecotoxicity	species.yr	4.93E-07	0.0598
Marine eutrophication	species.yr	6.16E-09	4.32E-08
Water consumption, Terrestrial ecosystem	species.yr	6.92E-07	6.92E-07
Freshwater eutrophication	species.yr	1.40E-07	3.26E-05
Ozone formation, Terrestrial ecosystem	species.yr	5.41E-05	7.01E-05
Ionizing radiation	DALY	3.83E-05	3.19E-05
Ozone formation, Human health	DALY	8.32E-05	0.000494
Water consumption, Human health	DALY	0.00011	0.000112
Terrestrial acidification	species.yr	9.61E-05	0.000193
Marine ecotoxicity	species.yr	0.00028	3.42
Human carcinogenic toxicity	DALY	0.00937	780
Global warming, Terrestrial ecosystem	species.yr	0.00109	0.000251
Stratospheric ozone depletion	DALY	0.00021	0.000199
Land use	species.yr	2.32E-05	2.32E-05
Fine particulate matter formation	DALY	0.092	0.105
Global warming, Human health	DALY	0.851	0.126
Human non-carcinogenic toxicity	DALY	0.372	2.64E04
Mineral resource scarcity	USD2013	0.200	0.202
Fossil resource scarcity	USD2013	1.46E03	2.77E03

Table 8. The results of damage categories for producing one ton of triticale production.

Damage category	Unit	Value (A_1)	Value (A_2)
Ecosystems	species.yr	2.68	3.48
Human health	DALY	1.07E04	2.72E04
Resources	USD2013	1.66E03	2.77E03

[a] DALY: disability adjusted life years. A damage of 1 is equal to loss of 1 life year of 1 individual, or 1 person suffers 4 years from a disability with a weight of 0.25.
[b] species.yr: the unit for ecosystems is the local species loss integrated over time.



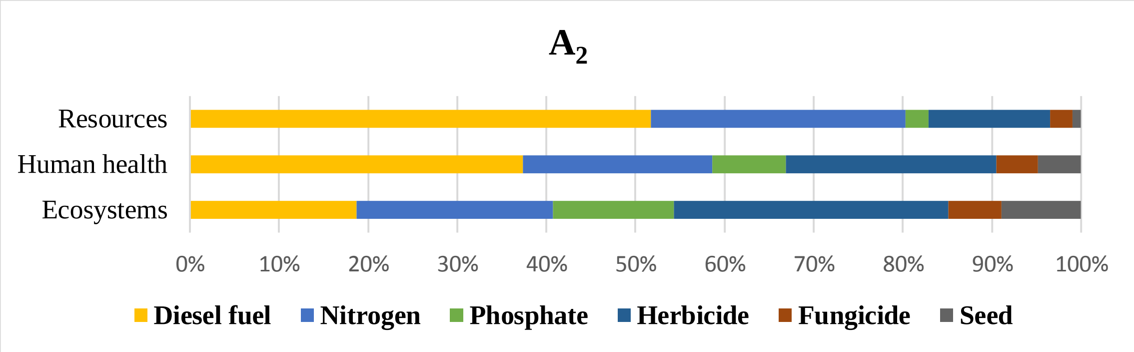


Figure 4. The share of damage categories by the inputs.

Conclusion

Statistics and research findings on the determination of energy consumption for agricultural products indicate unfavorable energy efficiency and productivity. Implementing management tools based on the scientific principles of agriculture can foster a positive trend in the field. It is crucial to minimize input waste by reducing energy and environmental emissions from production inputs. To curb fuel consumption, traditional operations that are unnecessary should be eliminated, and innovative methods should be adopted. Variable rate technologies, which tailor inputs to the specific needs of the farm, offer a promising solution for energy management. The growing demand for renewable energy has prompted societies to seek sustainable and renewable sources. Life Cycle Assessment (LCA) is a valuable tool for assessing the sustainability of renewable energy sources. Consequently, the utilization of phosphorus-solubilizing bacteria was demonstrated to reduce environmental emissions in triticale cultivation.

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