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Review Paper

Improving Energy Efficiency in Agronomical Systems

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A B S T R A C T

Increasing demand for agricultural products and production of resource constraints- especially the limitation of cultivable areas - have made the highest yield per unit area the main goal of agricultural producers. Agriculture is a system exhibiting high energy consumption and production. Since energy has a direct impact on the efficiency of crop production, a sustainable agricultural system needs to be analyzed in terms of its input and output energy to determine the total consumed energy of production per unit area. The difference between input and output energy determines energy efficiency of an agronomical system. Input energy requires being well analyzed to reduce energy consumption and increase energy efficiency. This paper reviews energy efficiency indices based on energy consumption during planting and harvesting. To enhance energy efficiency of agronomical systems, some strategies are discussed in detail, including using high quality seeds, minimum tillage systems, direct seeded rice, weeds control especially in irrigation canals and plant nutrition through agronomical management. Although some agronomical strategies -like complementary irrigation in dry land farming systems- increase input energy, they increase crop yield. However, when output energy, resulting from the rise in crop yield, is higher than input energy, the system energy efficiency improves. Still, some inputs cannot be altered according to regional conditions which are often related to harvest stages operations.

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INTRODUCTION

Since the invention of agriculture and more exploitation of solar energy, humans have been able to use renewable resources more efficiently [1]. Advances in manufacturing of agricultural equipment have resulted in more energy consumption in agriculture. Nowadays, agriculture is heavily dependent on energy [2]. Energy consumption in agricultural systems is more pronounced in developed countries; thanks to widespread use of agricultural machinery. However, in developing countries due to the transition from traditional farming to mechanized agriculture, energy use also increases [3, 4]. It is reported that using high yield cultivars, intensive farming systems, high application of fertilizers and pesticides and high level of mechanization resulted in high energy consumption in agronomical systems [5, 6].

Agriculture is a system exhibiting higher energy consumption compared to other economic sectors [5]. In fact, agronomical fields are ecosystems which consume high energy [6]. Nevertheless, limitation in renewable resources as well as environmental considerations is factors necessitating efficient use of energy in agronomical systems. Detailed determination of energy input is crucial for increasing energy efficiency in agronomical systems [1]. In other words, energy use in agronomical systems should be as efficient as possible requiring precise knowledge of energy resources. An accepted method for assessing energy consumption in agricultural systems is accurate calculation and analysis of input and output energy of agricultural production systems [6].

It is clear that energy shortage leads in crisis in agriculture. Energy crisis means the shortage of fertilizers and pesticides, the failure of irrigation pumps and planting and harvesting and transporting machineries bring about the reduction of crops. Therefore, evaluation of energy consumption is essential for improving energy

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efficiency in agronomical system through reducing input energy and increasing output energy. The current article is aimed assessing energy consumption by different inputs and introducing solutions to achieve high efficient agroecosystems in terms of energy.

KIND OF ENERGY CONSUMPTION IN AGROECOSYSTEM

In general, energy consumption in agronomical systems can be classified in three periodical sections: before planting, after planting, and after crop harvesting [1]. Energy consumed during these three phases can be renewable or non-renewable (Figure 1).

- Energy consumption before planting: it includes energy requirements for construction of agricultural machineries, fertilizers and pesticides, energy requirements for seed preparation (for example seed cleaning process), energy consumed for water supply facilities, and energy consumed during transporting [7].
- Energy consumption for crop planting: it includes all energy consumed for seed bed preparation, seed sowing, crop nutrition through application of fertilizers, crop protection by using pesticides and energy needed for plant harvesting (like human labor, machinery and diesel fuel) [1].
- Energy consumption after crop harvesting: energy consumed for transporting, packaging and storage of agricultural products falls into this category [8, 9].

Kenndy [10] reached to this result that machinery and diesel fuel were the inputs consuming the highest amount of energy in wheat production. They also observed that greater energy consumption did not result in more wheat production. Yelmen et al. [11], working with the energy efficiency of cotton fields, concluded that the input exhibiting the greatest energy consumption was diesel fuel, followed by human labour and machinery. In Iran, in the Khorasan Razavi province the total energy input for sugar beet production system was devoted to irrigation [12]. It was concluded that omitting consumed energy for irrigation can result in the increased energy efficiency of a sugar beet production system by more than two-fold. It is reported that the energy efficiency of potato production fields depends upon the degree of the mechanization of the production system [13]. Although mechanization of agricultural system improve the production, the increase in mechanization, increased the energy demand in agriculture as well [14]. However, for wheat production in dryland farming, reducing input energy has considered as main factor for improving energy efficiency [15].

The return of energy in a crop production system is related to different factors, including plant species, the kind of tillage system, the type of machinery, the mechanization rate of the production system and the size of farm [16–22]. Therefore, the current experiment sought to analyse the energy flow of the irrigated wheat production system for the possible improvement of the energy efficiency of the system.

ENERGY ASSESSMENT IN AGRONOMICAL SYSTEMS

There are some indicators used in the evaluation of energy efficiency of agronomical systems. These indicators are not only beneficial to evaluation of energy consumption in different parts of a production system, but also are efficiently used in comparison of several production systems. With the help of energy efficiency indicators, it is possible to recognize the cause of high energy consumption in agronomical systems during different stages of plant production [7].

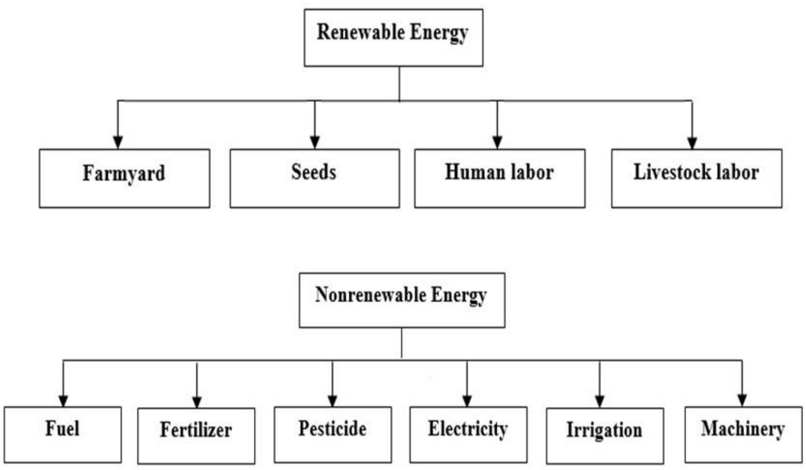

Figure 1. Kinds of consumed energy in agronomical systems regarding their renewability

Energy ratio

This energy efficiency index is calculated by the following equation:

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

In which ER is energy ratio, E_{out} is output energy (energy produced by crop yield) and E_{in} is input energy (energy consumed during all stages of crop production). Energy ratio has no unit. Energy ratio indicates how much energy will be produced with the consumption of every MJ energy per hectare. Higher energy ratios show higher efficiency of the system in terms of energy. Thus, higher energy ratio is favorable [6].

Net output energy

The following equation is used in measuring net output energy:

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

where NEG is net output energy, E_{out} is output energy (energy produced by crop yield) and E_{in} is input energy (energy consumed during all stages of crop production). Net output energy can have negative or positive amount. When input energy is more than output energy, net output energy is negative, showing that energy gained from crop yield could not compensate for the energy consumed in crop production. In such a condition, the system is not efficient in terms of energy. Positive and higher net output energy is favorable. Net energy input unit is MJ/ha [6].

Energy productivity

Energy productivity index, in terms of kg/MJ, shows the amount of produced yield per unit of consumed energy. Energy productivity is calculated using the following equation:

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

In which EP is energy productivity, Y is crop yield in terms of kg/ha and E_{in} is input energy (consumed energy) with the unit of MJ/ha. When two production systems with the same crop are compared with each other, higher energy productivity indicates that agronomic system produced higher yield per unit of consumed energy. It is clear that an agronomical system with higher energy productivity has a greater energy efficiency [9].

Special energy

Special energy is a reverse of energy productivity, showing consumed energy per produced yield. The unit of special energy is MJ/kg. Lower special energy, which shows lower energy consumption for production of a unit of crop yield, is favorable. Special energy is measured via the following equation [5]:

$$SP = Ein/Y \quad (4)$$

In Equation (4) EP is energy productivity, Y is crop yield in terms of kg/ha and E_{in} is input energy (consumed energy) with the unit of MJ/ha [5].

ENERGY MANAGEMENT DURING CROP PRODUCTION STAGES

Planting

Seed bed preparation

The Energy which is consumed for seed bed preparation including machinery, diesel fuel and human labor. A large proportion of input energy is usually allocated to seed preparation. Although improving mechanization for crop production leads to crop yield, it should be noted that there is not always a direct relationship between the level of mechanization and crop yield. In this case, two rice (*Oryza sativa*) production systems in Japan and United states were compared [10]. Rice production in Japan, where rice production is largely dependent on human labor, needed 640 of hours human labor per hectare, being equivalent to 1255 MJ/ha energy. However, mechanized production systems of the United States required only 24 of hours human labor per hectare which is equivalent to 47 MJ/ha energy consumption. While the two production systems produced similar grain yield, energy efficiency in Japan and USA was 2.8 and 1.2, respectively, suggesting the higher energy efficiency of rice production systems in Japan [10]. It seems that mechanization level should be reduced in order to increase energy efficiency of rice production systems in USA, because high energy consumptions of machinery and diesel fuel reduce energy efficiency of rice cropping systems.

The type of machinery has a substantial impact on energy consumption in seed bed preparation stage. In this case, five methods of seed bed preparation for wheat production were compared in a research [9]: 1. Moldboard plow, roller and seed drill 2. Chisel, roller and seed drill 3. Cycle tiller, roller and seed drill 4. Swipe, roller and seed drill and 5. Minimum tillage system. The result of this experiment revealed that the highest wheat grain yield was achieved with the fourth seed bed preparation method. Using moldboard plow resulted in the lowest grain yield of wheat. The highest and the lowest energy required for producing a crop unit yield were 8.8 and 11.8 allocated to the first and the fifth methods, respectively. Planting with moldboard plow, roller and seed drill and minimum tillage system allocated 32.5% and 19% of total input energy to wheat production system [9]. It can be concluded from this research that minimum tillage lessened energy consumption in machinery and diesel fuel sectors; and since grain yield achieved in this method was not the lowest, its energy efficiency was higher than other seed bed preparation methods.

Reduction of machinery usage is an effective way to enhance energy efficiency through seed bed preparation management. In has been reported that energy efficiency of rice production can be improved by direct seeding of rice [10]. In this method, some operations for nursery preparation would not be included which is influential in total energy efficiency of the system. However, grain production is not directly related to the amount of the energy consumed in this planting stage.

Seed sowing

Seed quality has a fundamental role in producing high crop yields. Seeds are considered high quality when their germination percentage, germination speed, vigor, health and purity (physical and genetic purity) are in high standards level. Germination and seedling establishment are critical stages in plant life cycle. In crop production, stand establishment determines plant density, uniformity and management options [11]. In crop species without tillering capacity, the importance of seed quality is more than other crop species.

When low quality seeds are sown in the field, it is necessary to sow more seeds to reach optimum plant densities, increasing energy consumption in terms of seed usage; for example, optimum plant density of wheat is obtained by using 160 kg/ha seeds [8]. If germination percentage of seed lot is 10% lower than standard level (90% means 90 seeds will germinate and establish by sowing 100 seeds), it needs to sow 18 kg/ha more seeds, pointing to the consumption of 362 MJ/ha energy (energy equivalent for some crop species is introduced in Table 1) [8].

On the other hand, low seed purity also results in higher energy consumption. For instance, when seed purity is 90% (caused by solid materials like sand), 362 MJ/ha more energy is consumed to reach the optimum plant density. If lower purity is caused by weed seeds, more energy is required since weed seeds will germinate later and chemical control will be required, which increases energy consumption. Thus, by reducing seed quality to 90% germination and 90% purity, 724 MJ/ha more energy will be consumed to reach the optimum plant density. This decreases energy efficiency of the systems because it increases input energy and has no effect on output energy of the system. It can be strongly emphasized that to reach high energy efficiency, high seed quality should be used in the agronomical systems.

Since different crop species have different seed energy equivalent, total energy consumption is also differently affected by the seed. Higher seed energy equivalent means higher energy consumption when it is needed to sow higher seed amount. For example, seed

Table 1. Energy equivalent of some crop species seeds

Crop Species	Seed Energy Equivalent MJ/Kg)	Reference
Rice (*Oryza sativa*)	14.7	[13]
Barley (*Hordeum vulgrare*)	14.7	[14]
Rapeseed (*Brassica napus*)	21.7	[15]
Wheat (*Triticum aestivum*)	20.1	[15]
Maize (*Zea mays*)	14.7	[16]
Alfalfa (*Medicago sativa*)	6.9	[17]
Sesame (*Sesamum indicum*)	3.6	[18]
Cotton (*Gosypium sp.*)	11.8	[19]
Sunflower (*Helianthus annuus*)	27.2	[20]
Bean (*Phaseolus vulgaris*)	14.7	[21]
Faba bean (*Vicia faba*)	14.7	[21]
Chickpea (*Pisum sativum*)	14.7	[21]
Tomato (*Lycopersicum esculentum*)	1.0	[7]
Potato (*Solanum toberusom*)	132	[22]
Sugar beet (*Beta vulgaris*)	5.04	[21]
Soybean (*Glycine max*)	14.7	[19]
Sorghum (*Sorghum bicolor*)	14.7	[21]
Mung bean (*Vigna radiate*)	14.7	[21]
Safflower (*Carthamus tinctorius*)	25.0	[21]

tubers of potato have higher energy equivalent than those of wheat. Thus, consumption of 10 kg/ha tuber seeds of potato leads to 1320 MJ/ha energy consumption. However, seed sowing in some species is more sensitive than the others regarding their energy consumption [6].

ENERGY MANAGEMENT DURING CROP GROWTH IRRIGATION

In some crop species like sugarcane [23], sugar beet [24] and rice [25] the highest energy consumption of production system is allocated to irrigation. It has been reported that in a sugar beet production system, more than 63% of total consumed energy of the system is consumed by irrigation, where energy efficiency of the system with the consideration of energy consumed by irrigation was 2.5-3.4, while it increased to 7.1-9.2 when energy equivalent of irrigation was not considered. Therefore, in order to increase energy efficiency of the agronomical ecosystems, irrigation should be as efficient as possible. An efficient way to increase energy efficiency of rice cultivation system is using direct seeded rice system in which no nursery is prepared and no irrigation occurs at least for 30 days, which can reduce 40% of total input energy [26].

Although crops are not irrigated in dry land farming systems, complementary irrigation can lead to the improvement in energy efficiency of the system. In this case, it has been reported that in barley dry land farming system, a complementary irrigation at flowering stage added 683 MJ/ha to total consumed energy. However, the increase in grain yield caused by complementary irrigation was 48%, which improved energy efficiency of the system more than 45% [27].

Irrigation management in source of irrigation and the way of water translocation to the field are also effective in total energy efficiency of the system, where it has been reported that using surface water resources increased energy efficiency of rice production system [20]. In most agronomical systems, water supply networks have no cover, which reduces water reaching to the field due to evaporation and water consumption by weeds, thus, downgrading energy efficiency of the system.

Pesticide usage

Most agronomical systems depend on pesticides to attain optimum yield. However, to increase energy efficiency of agronomical systems, pesticides usage needs to be well managed. Pesticides usage should be reduced, where factors resulting in lower application of pesticides develop the efficiency of the system in terms of energy. Crop rotation, intercropping, and biological pest management are efficient methods to decrease pesticides usage. Yet some methods which are effective in some systems, may not be useful in others. For example in a research it has been found that while biological control of orange aphids consumed lower energy compared to chemical control, white flies of cucumber and tomato horn worm should be chemically controlled in order to reach the higher energy efficiency of the system [28]. In spite of this, in some agronomical systems, reducing pesticides may result in improving energy efficiency of the system, while in some other cases high energy efficiency cannot be achieved without using chemical pest controllers.

Nutrient supply

High energy is consumed through fertilizers to supply crop plants with essential nutrients, where in some agronomical systems like sunflower [15] and potato [29] fertilizers comprise the highest energy consumer input.

Since fertilizers consume high energy; any reduction in the application of fertilizers will increase the energy efficiency of the system efficiently. An effective way to reach this goal is organic farming in which no fertilizer is used as a nutrient source. In organic farming, nutrients are supplied by agronomical management such as crop rotation in which crops of legominosae family are very important, because they add nitrogen (through biological nitrogen fixation process) to soil. For example, it has been reported that in an alfalfa production system, the lowest energy consumption belonged to the fertilizer (only 4.9% of the total consumed energy) induced by the ability of alfalfa in biological fixation of nitrogen [30]. Furthermore, alfalfa remains have a considerable content of nitrogen, which can help reduce fertilizer usage in the next crop. It is discovered that in cotton, watermelon, sesame and maize cropping systems, fertilizers comprised 50% of total energy input of the system. Hence, fertilizers play a major role in increasing energy efficiency of the agronomical systems, because of their proportion in total input energy of the systems. Organic fertilizers are good sources of nutrient and, therefore, an important factor in improving energy efficiency.

Farmyard manure and chemical fertilizer were compared in a study in terms of their economic and energy efficiency impacts. Results of this experiment revealed that farmyard manure costs more, but reduces energy consumption for 36-52% in comparison with the chemical fertilizers [31].

HARVESTING AND TRANSLOCATION

Some factors such as machinery, diesel fuel, and human labor affect input energy in the harvest and translocation sectors. However, the amount of their impact on energy consumption depends on the kind of cropping system. Increasing mechanization changes the kind of energy consumption. For instance, in dry land farming systems where it is not possible to harvest crops by machineries, human labor consumes the highest energy. It seems that energy consumption in this sector is constant for each field and region. As a result, it may not be possible to enhance energy efficiency of the system by modifications in this sector. In spite of this, lubrication of machineries can reduce energy consumption, somewhat increasing energy efficiency [32–34].

CONCLUSION

In all stages of crop planting, it is possible to improve energy efficiency of the agronomical systems through reducing energy consumption by appropriate management of inputs. High quality seed lots, minimum tillage systems, direct seeded production of rice, weeds control in irrigation networks, and agronomical approaches for nutrient supply like intercropping and rotation are important methods to reduce input energy. Although irrigation in dry land farming systems accompanied by the rise in energy consumption, high grain yield induced by complementary irrigation shows the increase the energy efficiency of the system. It is essential note that some inputs cannot be change to for energy efficiency as a result of their dependency on the region and field conditions.

CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

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Persian Abstract

چکیده

افزایش نیاز برای محصولات کشاورزی و محدودیت منابع تولید –بویژه محدودیت در مناطق قابل کشت- باعث شده است که افزایش تولید در واحد سطح، هدف اصلی تولیدکنندههای کشاورزی باشد. کشاورزی سیستمی است که مقدار بالایی از مصرف و تولید انرژی را دارد. از آنجا که انرژی تاثیر مستقیمی بر تولید گیاهان زراعی دارد، یک سیستم کشاورزی پایدار باید از نظر انرژی‌های ورودی و خروجی مورد تجزیه و تحلیل قرار بگیرد تا میزان انرژی مصرف شده‌ی هر محصول در واحد سطح، تعیین شود. تفاوت انرژی ورودی و انرژی خروجی یک سیستم زراعی، میزان کارآیی انرژی آن را تعیین می‌کند. انرژی‌های ورودی باید به خوبی تجزیه و تحلیل شوند تا امکان کاهش مصرف انرژی و افزایش کارآیی انرژی فراهم شود. در این مقاله، شاخص‌های کارآیی انرژی بر اساس مصرف انرژی در طول دوره‌ی کاشت تا برداشت گیاهان زراعی مرور شده است. برای افزایش کارآیی انرژی سیستم‌های زراعی، برخی استراتژی‌ها شامل استفاده از بذور با کیفیت، کاهش سیستم‌های شخم، کشت مستقیم بذر در محصولاتی مانند برنج، کنترل علف‌های هرز بخصوص در کانال‌های آبیاری و تغذیه گیاه از طریق مدیریت‌های زراعی مورد بحث قرار گرفته است. اگر چه برخی استراتژی‌های زراعی –مانند آبیاری تکمیلی در سیستم‌های زراعی مناطق خشک- انرژی ورودی به سیستم را افزایش می‌هد ولی باعث افزایش عملکرد دانه گیاهان زراعی می‌شوند. به هر حال، وقتی انرژی خروجی، ناشی از افزایش عملکرد گیاه، بیشتر از انرژی ورودی باشد، کارآیی انرژی سیستم بهبود می‌یابد. با این حال، هنور برخی انرژی‌های ورودی، بر اساس شرایط منطقه‌ای که عمدتاً به مرحله‌ی برداشت مرتبط هستند، قابل تغییر نمی‌باشند.