INTRODUCTION

Energy is a global and strategic issue related to the development of human society and the international political and economic situation. Continuous advancement of industrialization and the continuous increase in the world population, the constraints of energy on human development are increasingly strengthened, and the problem of energy security...
is becoming increasingly serious. Studies have shown that global energy demand is expected to increase from the current 472 trillion Btu to 678 trillion Btu by 2030 (EIAU, 2009). Ultimately, the energy problem is about energy utilization, and the key to solving this problem is finding an effective way to improve energy production efficiency.

Energy consumption in agricultural production accounts for a large share of the world’s total energy consumption. With ongoing economic and societal development, and the continuous advancement of agricultural modernization, agricultural production is increasingly energy-dependent (including fertilizers, electricity, and diesel), and resources and environment constraints are also accordingly strained (Cao et al., 2010; Karkacier et al., 2006; Khoshnevisan et al., 2013; Pirdashti et al., 2015). In the current context of growing pressure on resources and the environment, extensive agricultural production methods that promote agricultural economic growth solely through the input of a large number of agricultural production factors are unsustainable. Changing the method of agricultural development, banning high-energy-intensive and inefficient methods of agricultural production, and developing an energy-saving and environmentally friendly modern agricultural production system is an effective way to alleviate the contradictions between "demand and supply of resources" and "agricultural production and the environment", and is also the inevitable direction of current agricultural development.

Rice and wheat are both important world food crops (Ladha et al., 2003), and rice–wheat rotation is one of the major food crop systems globally (Prasad, 2005), which is mainly found in East Asia and South Asia, with a cultivated area of approximately 26 million ha (Timsina & Connor, 2001), providing a stable source of food for more than 20% of the world’s population (Kumari et al., 2011; Prasad, 2005). Therefore, the high and stable yields of rice–wheat rotation systems are of great impact for ensuring regional and even world food security (Jin et al., 2020). During the transition period in the modernization of agricultural production, the structure of the rural labor force changed. Influenced by labor shortages, rising labor costs, and the development of agricultural production toward scale and intensification, the light simplification and intensification of rice production have once again become the focus of farmers. Currently, there are two main methods of rice cultivation: transplanting and direct seeding. Compared with seedling transplanting, direct seeding of rice eliminates the need for planting, pulling, and transplanting and has advantages such as labor and cost savings, and efficiency increases (Tao et al., 2016).

A great deal of research has been done on rice–wheat rotation, but relevant research on the energy balance of different rice–wheat rotation systems has rarely been reported. Understanding the energy consumption pathways and their consumption amount in rice–wheat rotation systems will help to explore ways to reduce the amount of energy input in rice–wheat rotation production and improve energy production efficiency. This approach is not only beneficial for ensuring world food security, but is also conducive to reducing energy consumption in agricultural production, diminishing damage to the ecological environment, and maintaining sustainable agricultural development. Therefore, this study aims to analyze the energy budget and energy production efficiency of different rice–wheat rotation systems, to provide theoretical guidance for the establishment of low energy consumption and high energy efficiency rice–wheat rotation production systems.

2 | MATERIALS AND METHODS

2.1 | Experimental site

The experiments were conducted in the modern agriculture demonstration park (112°21′E, 32°7′N) in Xiangzhou District, Xiangyang City, Hubei Province from 2018 to 2020. Xiangyang belongs to the subtropical humid monsoon continental climate, which is characterized by four distinct seasons, rain and heat in the same season, with an average annual temperature of approximately 15.3°C, an average annual sunshine time of 2000 h, an annual frost-free period of 243 days, and an average annual precipitation of 878.3 mm. The soil of the test site was submerged rice soil with medium fertility, and the pH, organic matter, alkaline nitrogen, available phosphorus, and available potassium in the upper 20 cm of soil were 6.4, 17.11 g kg⁻¹, 72.66 mg kg⁻¹, 15.85 mg kg⁻¹, and 106.18 mg kg⁻¹, respectively.

2.2 | Experimental details

Three rice planting methods were tested: dry direct-seeded rice (DSR), wet direct-seeded rice (WSR), and transplanted rice (TR). The tested variety in the rice season was Huhan15 and the tested variety in the wheat season was Zhengmai9023. The experimental design was a completely randomized block design with 4 repetitions and the plot area was 36 m². Dry direct-seeded rice plots were prepared under drought conditions, and wet direct-seeded and transplanted rice plots were prepared after irrigation and soil soaking. The fertilizer application rates in the rice season were N 150 kg ha⁻¹ in the form of urea, P₂O₅ 67.5 kg ha⁻¹ in the form of calcium superphosphate, K₂O 100 kg ha⁻¹ in the form of potassium chloride, and Zn 2 kg ha⁻¹ in the form of zinc sulfate, in which phosphorus, potassium, and zinc fertilizers were applied at one time as basic fertilizer, and nitrogen fertilizer was applied in the ratio of basic fertilizer: tiller fertilizer: panicle initiation fertilizer: panicle fertilizer = 2:2:1:1. The sowing rate of
the direct-seeded rice was 60 kg ha⁻¹, the row spacing was 25 cm, and the seeding method was machine sowing. The transplanted rice was germinated before sowing until the buds grew approximately 0.5 cm, and then was transplanted when the seedlings were 20 days old. The seedlings were transplanted at a hill spacing of 25 × 16 cm with four seedlings per hill. Dry direct-seeded rice is mainly rain-fed, and when the soil is too dry (soil water potential ≤ −30 kPa), moist irrigation is carried out to keep the soil aerobic throughout the rice-growing season. The water layer was kept at 3–10 cm in the plots of wet direct-seeded rice from 4.5 leaves until 2 weeks before rice harvest. After transplantation of rice seedlings, the plots were kept in a 3–10 cm water layer until 2 weeks before rice harvest.

After rice harvest, the aboveground rice stubble was removed, and then the soil was plowed evenly with a rotary tiller to plant subsequent wheat at a sowing rate of 180 kg ha⁻¹ with a row spacing of 18 cm, the seeding method was machine sowing. The fertilizer application rates in the wheat season were N 180 kg ha⁻¹, P₂O₅ 120 kg ha⁻¹, K₂O 90 kg ha⁻¹, and Zn 2 kg ha⁻¹; in which phosphorus, potassium, and zinc fertilizers were applied at one time as basic fertilizer, and nitrogen fertilizer was applied in the ratio of basic fertilizer: tiller fertilizer: jointing fertilizer = 2:1:1. The forms of N, P, K, and Zn fertilizers in wheat season were the same to those in rice season. There was strict control of diseases, insects, weeds, and birds during the whole growth season of rice and wheat in both years. Crop samples were collected from each plot during the maturity of rice and wheat to determine their economic and biological yields.

### 2.3 Energy analysis

The energy input, output, and production efficiency of three rice–wheat rotation systems, dry direct-seeded rice–wheat, wet direct-seeded rice–wheat and transplanted rice–wheat, were analyzed and compared. In this study, it was found that the energy inputs in rice–wheat rotation production included irrigation water, machinery, diesel, electricity, labor, seeds, fertilizers, and pesticides. Energy output included rice and wheat grains and their straws. Human energy and mechanical energy were calculated by multiplying the number of human labor hours and farm machinery hours used per hectare of farm production with their energy equivalent, respectively. While, the energy of diesel and irrigation water was calculated by multiplying the volume of diesel and irrigation water consumed per hectare of agricultural production by its energy equivalent. Similarly, electric energy and fertilizer energy were calculated by multiplying the electricity consumption and nutrient content of the various fertilizers used per hectare of agricultural production by their energy equivalent, respectively. Pesticide energy was also calculated in the same method. Seed energy was calculated by multiplying the amount of seed used per hectare of farmland by its energy equivalent, and the energy of crop straw and grain was calculated by multiplying the yield of crop straw and grain per hectare by its energy equivalent. The energy equivalents of each energy input and output item in the calculation are shown in Table 1. The total energy input was the sum of the energy of all inputs, and the total energy output was the sum of the energy of all outputs.

The net energy, energy use efficiency, energy productivity, energy profitability, and human energy profitability of the rice crop rotation system were then calculated based on the calculated energy inputs and outputs of each item and the total energy inputs and outputs in the rice and wheat production through the following equations (Pirdashti et al., 2015; Singh et al., 2019):

\[
\text{Net energy (NE)} = \text{Energy output (MJ ha}^{-1} \text{)} - \text{Energy input (MJ ha}^{-1} \text{)}
\]

(1)

\[
\text{Energy use efficiency (EUE)} = \frac{\text{Energy output (MJ ha}^{-1} \text{)}}{\text{Energy input (MJ ha}^{-1} \text{)}}
\]

(2)

\[
\text{Energy productivity (EP)} = \frac{\text{Crop yield (kg ha}^{-1} \text{)}}{\text{Energy input (MJ ha}^{-1} \text{)}}
\]

(3)

\[
\text{Energy profitability (EPF)} = \frac{\text{Net energy (MJ ha}^{-1} \text{)}}{\text{Energy input (MJ ha}^{-1} \text{)}}
\]

(4)

Human labor energy profitability (HEPF) = \frac{\text{Energy output (MJ ha}^{-1} \text{)}}{\text{Human labor energy (MJ ha}^{-1} \text{)}}

(5)

Generally, energy in agricultural production can be divided into renewable energy and nonrenewable energy. Renewable energy mainly includes human labor, seeds, irrigation water, wind, and hydroelectricity, while nonrenewable energy mainly includes fertilizers, pesticides, diesel, machinery, and thermoelectricity (Kazemi et al., 2015). The electricity used in China is mainly produced by thermal power, wind power, and hydropower. According to a previous report, in 2014, thermal power generation accounted for 75% of China’s total electricity production, and the remaining 25% of electricity was mainly derived from wind and hydropower (China’s Electricity Yearbook Committee, 2015).

### 2.4 Statistical analysis

Statistix 9 (Analytical Software) was used for statistical analysis of the data, the least significant difference method (LSD) was used for statistical analysis of the variance of the data at.
3 | RESULTS

3.1 | Energy input

Among the three rice–wheat rotation systems, the total energy input in descending order was the wet direct-seeded rice–wheat rotation system, the transplanted rice–wheat rotation system and the dry direct-seeded rice–wheat rotation system (Figure 1), and fertilizer and diesel were the two most energy-intensive inputs in the rice–wheat rotation system (Tables 2 and 3). Irrigation water consumption, diesel consumption, and machine use time during the rice season were much higher in the wet direct-seeded and transplanted rice–wheat rotation systems than in the dry direct-seeded rice–wheat systems. Thus, the two-year average total energy input of the wet direct-seeded and transplanted rice–wheat rotation systems was 16,080 and 9083 MJ ha⁻¹ more than of the dry direct-seeded rice–wheat rotation system, respectively, because the inputs of these three resources in the rice season were less than those of the wet direct-seeded rice–wheat rotation system, resulting in, compared to the wet direct-seeded rice–wheat rotation system, a decrease in the two-year average energy inputs of 6997 MJ ha⁻¹ in the transplanted rice–wheat rotation system (Tables 2 and 3 and Figure 1). In the dry direct-seeded rice–wheat rotation system, the greatest energy input was fertilizer, followed by diesel and machinery, and in the wet direct-seeded and transplanted rice–wheat rotation systems, the energy input in descending order was fertilizer, diesel, machinery, and irrigation water. The production resources with higher energy input in the dry direct-seeded rice were, from the most to the least, fertilizer, diesel, 

![Figure 1: The total energy input of different rice–wheat rotation systems. DSR-W, WSR-W, and TR-W indicate the dry direct-seeded rice–wheat rotation system, wet direct-seeded rice–wheat rotation system, and transplanted rice–wheat rotation system, respectively; error bars represent the SD, the same as below.](image-url)
TABLE 2  Resource input in the rice season and subsequent wheat season under different rice planting methods

| Year            | Growth season | Rice planting method | Irrigation water (m³ ha⁻¹) | Pesticide (kg ha⁻¹) | Electricity (kWh ha⁻¹) | Fertilizer (kg ha⁻¹) | Seed (kg ha⁻¹) | Human labor (h ha⁻¹) | Diesel (L ha⁻¹) | Machinery (h ha⁻¹) |
|-----------------|---------------|----------------------|---------------------------|---------------------|------------------------|---------------------|----------------|----------------------|----------------|------------------|
| 2018–2019       | Rice season   | DSR                  | 2639                      | 5.03                | 15.00                  | 320                 | 60.00          | 145                  | 191            | 67.87            |
|                 |               | WSR                  | 7417                      | 4.65                | 12.00                  | 320                 | 60.00          | 213                  | 294            | 162.15           |
|                 |               | TPR                  | 6583                      | 4.28                | 12.00                  | 320                 | 20.00          | 4433                 | 245            | 138.11           |
| Wheat season    | DSR           | 278                  |                           | 5.04                | 12.00                  | 392                 | 180.00         | 131                  | 166            | 25.94            |
|                 | WSR           | 278                  |                           | 5.04                | 12.00                  | 392                 | 180.00         | 131                  | 166            | 25.94            |
|                 | TPR           | 278                  |                           | 5.04                | 12.00                  | 392                 | 180.00         | 131                  | 166            | 25.94            |
| 2019–2020       | Rice season   | DSR                  | 2222                      | 5.03                | 15.00                  | 320                 | 60.00          | 1431                 | 185            | 60.15            |
|                 |               | WSR                  | 6667                      | 4.65                | 12.00                  | 320                 | 60.00          | 211                  | 2835           | 148.26           |
|                 |               | TPR                  | 4806                      | 4.28                | 12.00                  | 320                 | 20.00          | 4391                 | 219            | 105.19           |
| Wheat season    | DSR           | 278                  |                           | 5.78                | 15.00                  | 392                 | 180.00         | 1319                 | 166            | 25.94            |
|                 | WSR           | 278                  |                           | 5.78                | 15.00                  | 392                 | 180.00         | 1319                 | 166            | 25.94            |
|                 | TPR           | 278                  |                           | 5.78                | 15.00                  | 392                 | 180.00         | 139                  | 166            | 25.94            |

Note: DSR, WSR, and TPR indicate dry direct-seeded rice, wet direct-seeded rice, and transplanted rice, respectively, the same as below.

TABLE 3  Energy input of the rice season and subsequent wheat season under different rice planting methods

| Year            | Growth season | Rice planting method | Irrigation water (MJ ha⁻¹) | Pesticide (MJ ha⁻¹) | Electricity (MJ ha⁻¹) | Fertilizer (MJ ha⁻¹) | Seed (MJ ha⁻¹) | Human labor (MJ ha⁻¹) | Diesel (MJ ha⁻¹) | Machinery (MJ ha⁻¹) |
|-----------------|---------------|----------------------|---------------------------|---------------------|------------------------|---------------------|----------------|----------------------|----------------|------------------|
| 2018–2019       | Rice season   | DSR                  | 2692                      | 1090                | 179                    | 11,893              | 882            | 245                  | 10,761          | 4255             |
|                 |               | WSR                  | 7565                      | 1001                | 143                    | 11,893              | 882            | 370                  | 16,559          | 10,167           |
|                 |               | TPR                  | 6715                      | 911                 | 143                    | 11,893              | 294            | 714                  | 13,803          | 8660             |
| Wheat season    | DSR           | 283                  | 1073                      | 143                 | 14,418                 | 2646               | 220            | 9331                 | 1627            | 1627             |
|                 | WSR           | 283                  | 1073                      | 143                 | 14,418                 | 2646               | 220            | 9331                 | 1627            | 1627             |
|                 | TPR           | 283                  | 1073                      | 143                 | 14,418                 | 2646               | 220            | 9331                 | 1627            | 1627             |
| 2019–2020       | Rice season   | DSR                  | 2267                      | 1090                | 179                    | 11,893              | 882            | 241                  | 10,413          | 3772             |
|                 |               | WSR                  | 6800                      | 1001                | 143                    | 11,893              | 882            | 366                  | 15,934          | 8296             |
|                 |               | TPR                  | 4902                      | 911                 | 143                    | 11,893              | 294            | 706                  | 12,320          | 6596             |
| Wheat season    | DSR           | 283                  | 1232                      | 179                 | 14,418                 | 2646               | 233            | 9331                 | 1627            | 1627             |
|                 | WSR           | 283                  | 1232                      | 179                 | 14,418                 | 2646               | 233            | 9331                 | 1627            | 1627             |
|                 | TPR           | 283                  | 1232                      | 179                 | 14,418                 | 2646               | 233            | 9331                 | 1627            | 1627             |
and machinery. In the wet direct-seeded and transplanted rice–wheat rotation systems, the energy input in descending order was diesel, nitrogen fertilizer, machine, and irrigation water (Table 3), the highest proportion of nitrogen energy in all fertilizers. The energy input of subsequent wheat was the same for different rice planting methods, with an average of 29,846 MJ ha\(^{-1}\) in 2 years, and the energy input in descending order was fertilizer, diesel, and seed (Table 3). In addition, the energy input of wet direct-seeded rice accounted for the highest proportion of the total energy input of the rice–wheat rotation system, reaching more than 60% in both years, followed by transplanted rice, which accounted for more than 55%, and the energy input of the dry direct-seeded rice accounted for the lowest proportion of the total energy input of the rice–wheat rotation system, but it also reached more than 50%. This result showed that the key to improving the energy production efficiency in the rice–wheat rotation system may be by improving the energy production efficiency in the rice season.

The input of renewable energy in the three rice–wheat rotation systems was far less than that of nonrenewable energy (Table 4). The renewable energy input of the wet

| Year          | Rotation system | Rice season energy input (MJ ha\(^{-1}\)) | Wheat season energy input (MJ ha\(^{-1}\)) | Percentage (%) | Rice season energy input (MJ ha\(^{-1}\)) | Wheat season energy input (MJ ha\(^{-1}\)) | Percentage (%) | Rice season energy input (MJ ha\(^{-1}\)) | Wheat season energy input (MJ ha\(^{-1}\)) | Percentage (%) | Rice season energy input (MJ ha\(^{-1}\)) | Wheat season energy input (MJ ha\(^{-1}\)) | Percentage (%) |
|---------------|----------------|------------------------------------------|------------------------------------------|----------------|------------------------------------------|------------------------------------------|----------------|------------------------------------------|------------------------------------------|----------------|------------------------------------------|------------------------------------------|----------------|
| 2018–2019     | DSR-W          | 61,278                                   | 73,321                                   | 11.42          | 7048                                     | 12,038                                   | 15.37          | 3435                                     | 10,944                                   | 15.02          | 3185                                     | 10,944                                   | 10.94          |
|               | WSR-W          | 78,281                                   | 71,321                                   | 14.80          | 8852                                     | 12,038                                   | 14.02          | 3435                                     | 11,524                                   | 10.94          | 3185                                     | 11,524                                   | 10.94          |
|               | TPR-W          | 72,875                                   | 60,875                                   | 10.94          | 7759                                     | 10,944                                   | 14.02          | 3435                                     | 11,524                                   | 10.94          | 3185                                     | 11,524                                   | 10.94          |
| 2019–2020     | DSR-W          | 60,685                                   | 60,875                                   | 9.94           | 3435                                     | 10,944                                   | 10.94          | 3185                                     | 11,524                                   | 10.94          | 3185                                     | 11,524                                   | 10.94          |
|               | WSR-W          | 76,263                                   | 71,321                                   | 14.80          | 8084                                     | 12,038                                   | 15.37          | 3185                                     | 10,944                                   | 15.02          | 3185                                     | 10,944                                   | 15.02          |
|               | TPR-W          | 67,714                                   | 59,383                                   | 8.94           | 5938                                     | 9,145                                    | 15.20          | 3988                                     | 9,145                                    | 23.20          | 5938                                     | 9,145                                    | 23.20          |
direct-seeded rice–wheat rotation system was higher than that of the dry direct-seeded and transplanted rice–wheat rotation systems (Table 4). The dry direct-seeded rice–wheat rotation system had the lowest renewable energy input (Table 4). The two-year average renewable energy input of the wet direct-seeded rice–wheat rotation system was 11,664 MJ ha$^{-1}$, which accounts for the highest proportion of the total energy input in the rice–wheat rotation system, reaching 15.09%, with energy input from irrigation water alone accounting for more than 64% of the total renewable energy input. The two-year average renewable energy input of the transplanted rice–wheat rotation system was 10,045 MJ ha$^{-1}$, accounting for 14.29% of the total energy input of the rice–wheat rotation system, and the energy input of irrigation water also reached more than 60% of the total renewable energy input, while the two-year average renewable energy input of the dry direct-seeded rice–wheat rotation system was only 6845 MJ ha$^{-1}$, accounting for only 11.18% of the total energy input of the rice–wheat rotation system, and the energy input of seeds and irrigation water were the two largest parts of the renewable energy input, accounting for more than 91% of the total renewable energy input (Tables 3 and 4).

### 3.2 | Energy output

The total energy output and net energy in the transplanted rice–wheat rotation system were higher than those of the direct-seeded rice–wheat rotation system, and the net energy of the wet direct-seeded rice–wheat rotation system was the lowest among the three rice–wheat rotation systems (Figure 2). The energy output of the transplanted rice–wheat rotation system was higher in both the rice season and the wheat season, and the energy input was relatively low, so the average total energy output and net energy were 26,492 and 25,449 MJ ha$^{-1}$ more than those of the direct-seeded rice–wheat rotation system, respectively (Figure 2). The energy output of the two direct-seeded rice–wheat rotation systems was similar, but the energy input of the wet direct-seeded rice was 51.27% more than that of the dry direct-seeded; thus, the net energy of the dry direct-seeded rice–wheat rotation system was 15,227 MJ ha$^{-1}$ more than that of the wet direct-seeded rice–wheat rotation system (Figure 2). The energy output structure of different rice–wheat rotation systems was different. In the dry direct-seeded rice–wheat rotation system, the energy output of the wheat season was more than that of the rice season, while in the wet direct-seeded and transplanted rice–wheat rotation systems, the energy output of the rice season was more than that of the wheat season (Figure 2). The structure of net energy in different rice–wheat rotation systems differed between 2 years. In the dry direct-seeded rice–wheat rotation system, the net energy was more in the rice season than in the wheat season, and in the wet direct-seeded rice–wheat rotation system, the net energy was more in the rice season than in the wheat season (Figure 2). However, the net energy structure of the transplanted rice–wheat rotation system differed between 2 years. In 2018–2019, there was more net energy in the wheat season than in the rice season, while in 2019–2020, there was more net energy in the rice season than in the wheat season (Figure 2).

### 3.3 | Energy production efficiency

The highest energy use efficiency, energy productivity, energy profitability, and human energy profitability were observed in the dry direct-seeded rice–wheat rotation system, while the transplanted rice–wheat rotation system had higher energy use efficiency, energy productivity, and energy profitability than the wet direct-seeded rice–wheat rotation system, and the human energy profitability of the wet direct-seeded rice–wheat rotation system was higher than that of the transplanted rice–wheat rotation system (Table 5). The total energy input of the dry direct-seeded rice–wheat rotation system was less, while the total energy output of the transplanted rice–wheat rotation system was high; thus, the average energy use efficiency and energy profitability of these two rice–wheat rotation systems reached 6.74 and 6.27 and 5.74 and
5.27, respectively, which was higher than the 5.35 and 4.35 of the wet direct-seeded rice–wheat rotation system (Table 5). The energy productivity of the dry direct-seeded rice–wheat rotation system reached 0.26 kg MJ⁻¹, followed by 0.25 kg MJ⁻¹ for the transplanted rice–wheat rotation system. The wet direct-seeded rice–wheat rotation system had the lowest energy productivity, only 0.21 kg MJ⁻¹. The energy productivity of the dry direct-seeded rice–wheat rotation system was 26.83% higher than that of the wet direct-seeded rice–wheat rotation system (Table 5). Although the total energy output of the transplanted rice–wheat rotation system was higher than that of the direct-seeded rice–wheat rotation system, its average human energy input was also 99.46% and 57.66% higher than that of the dry direct-seeded and wet direct-seeded rice–wheat rotation systems, respectively. Its human energy profitability was only 469, which was lower than the 878 of the dry direct-seeded rice–wheat rotation system and the 695 of the wet dry direct-seeded rice–wheat rotation system, respectively (Table 5).

4 | DISCUSSION

The total energy input of different rice–wheat rotation systems was mainly influenced by the energy input in the rice season, which is mainly related to the irrigation amount (Rao et al., 2018). And the amount of diesel consumed for irrigation and the use time of pump were positively correlated with the irrigation amount. Some studies have shown that energy consumption for irrigation operations accounts for 71% of the total energy consumption in irrigated agriculture (Safa et al., 2011). Different rice planting methods have different water management methods. During the growth period of dry direct-seeded rice, the soil of the paddy field was kept aerobic, and humid irrigation was only performed during extreme drought, so irrigation consumes less energy. In contrast, the water management methods of wet direct-seeded and transplanted rice were similar, but the field growth period of transplanted rice was shorter, so the irrigation amount was also less than that of wet direct-seeded rice. The energy input of subsequent wheat was the same for different rice planting methods, which is less than the energy input in Iranian wheat production (Ghorbani et al., 2011; Shahan et al., 2008), but more than the energy input in Canadian, Indian, Italian, and New Zealand wheat production (Ali et al., 2013; Safa & Samarasinghe, 2011; Singh et al., 2007; Zentner et al., 2004). Different from the structure of energy input in the rice season, the production resources with more energy inputs in the wheat season were fertilizer, diesel, and seed, respectively, which was due to less irrigation in the wheat season. Fertilizers consume a large proportion of the total energy input in rice and wheat production (Freedman, 1980; Khan et al., 2009; Mandal et al., 2002; Safa et al., 2011), and the energy consumption of nitrogen fertilizer accounts for the highest proportion of all fertilizers, which was consistent with previous studies (Kazemi et al., 2015; Yuan & Peng, 2017). The energy input of the rice season accounts for more than 50% of the total energy input of the rice–wheat rotation system, which indicates that the key to improving the energy production efficiency in the rice–wheat rotation system may be by improving the energy production efficiency in the rice season. Studies have shown that optimizing the management methods of water and fertilizer can reduce the amount of water and fertilizer without reducing rice yield (Fan et al., 2012; Peng et al., 2010; Tao et al., 2016). According to the results of this study, the production resources with more energy input in rice production were all related to water and fertilizer, so reducing the amount of water and fertilizer is an important way to reduce the total energy input in the rice–wheat rotation system.

Agricultural production relies heavily on the input of non-renewable energy sources such as diesel, chemicals, fertilizers, and machinery (Gundogmus, 2006; Mohammadi et al., 2008; Pishgar-Komleh et al., 2011). Our results also demonstrate that non-renewable energy input was much more than renewable energy in rice–wheat rotation production, which is similar to other studies in rice, tomato, grape, and watermelon production (Esengun et al., 2007; Khan et al., 2009; Mohammadi-Barsari et al., 2016; Ozkan et al., 2007). Irrigation water energy accounts for a large proportion of the total renewable energy input in rice–wheat rotation system, but there was a great difference in irrigation amount in different rice–wheat rotation systems. Our study shows that the energy in irrigation water accounts for more than 60% of the total renewable energy input in the wet direct-seeded and transplanted rice–wheat rotation systems, and more than 40% of the total renewable energy input in the dry direct-seeded rice–wheat rotation system. This shows that there was still a great application space of renewable energy in agricultural production. In order to reduce the threat of agricultural production to energy and ecological security and improve the sustainability of agricultural production, it is necessary to reduce the energy input in agricultural production and increase the proportion of renewable energy input in the total energy input of agricultural production through production technology innovation, which is also one of the future research directions of agricultural workers (Yuan & Peng, 2017; Zangeneh et al., 2010).

Some studies have found that the energy output of irrigated rice was 1.5 times higher than that of rain-fed rice (Soni & Soe, 2016). In this study, the energy output of wet direct-seeded rice was only 1.14 times that of dry direct-seeded rice, which may be due to the fact that dry direct-seeded rice was not completely fed by rain, and wet irrigation was carried out in the extreme drought. The different contribution structure of net energy in the two-year transplanted rice–wheat rotation
system may be influenced by the soil water retention of the experimental field. The higher topography of the 2018–2019 experimental field and the higher sandy loam content of the soil with poor water retention resulted in more irrigation in its rice season than in the 2019–2020 rice season. The difference in energy output between wet direct-seeded and transplanted rice was small in 2018–2019, while the energy output of transplanted rice was significantly more than that of wet direct-seeded rice in 2019–2020. This situation occurred because the 2019–2020 wet direct-seeded rice encountered extreme high temperature (the maximum daily temperature ≥35°C, Figure 3) during the heading period, which caused some spikelets to abort and the number of grains per panicle decreased (Farrell et al., 1997; Matsui et al., 1997; Shah et al., 2011; Xiao et al., 2011). At the same time, due to the abortion of spikelets, the storage capacity became smaller, and a large amount of dry matter cannot be transferred to the grain and stored in the straw, leading to a lower harvest index of rice, while the energy equivalent of rice straw is lower than that of the rice grain, which eventually leads to the reduction of energy output.

Energy use efficiency is one of the best indicators for conducting input–output energy analysis of crop production, which could indicate the extent of efficient energy use (Yuan & Peng, 2017). Energy productivity is an indicator that can be used to determine the environmental impacts associated with crop production (Kazemi et al., 2015), and some studies have shown that the indicator can be used to determine the optimal land use and crop management intensity (Hulsbergen et al., 2001). The energy use efficiency, energy productivity, energy profitability, and human energy profitability of the dry direct-seeded rice–wheat rotation system in this study were higher than those of the wet direct-seeded and transplanted rice–wheat rotation systems. This is mainly due to the significant reduction in its energy input (mainly irrigation water, diesel, machine use time, and human labor). The energy use efficiency, energy productivity, and energy profitability of the transplanted rice–wheat rotation system were higher than those of the wet direct-seeded rice–wheat rotation system mainly because of its higher energy output. However, the human energy profitability of the wet direct-seeded rice–wheat rotation system was higher than that of the transplanted rice–wheat rotation system mainly because of the lower human energy input in the wet direct-seeded rice–wheat rotation system. The above research results indicate that the energy use efficiency, energy productivity, energy profitability, and human energy profitability of the rice–wheat rotation system can be significantly improved by optimizing the cultivation and water management methods, which is also the basic direction of the research on low energy consumption and high energy efficiency agricultural production in the future.

5 | CONCLUSION

This study evaluated the energy input and output of three rice–wheat rotation systems and their energy production efficiencies. The results of the study showed that the wet direct-seeded rice–wheat rotation system had more total energy

Figure 3: Temperature during the rice growth seasons in 2018 and 2019.
input than the dry direct-seeded and transplanted rice–wheat rotation systems. Among the three rice–wheat rotation systems, fertilizer and diesel are the two most energy-intensive components. In the rice–wheat rotation system, the energy input of the rice season accounts for more than 50% of the total energy input of the system, so reducing the energy input of the rice season is the key to reducing the energy input of the rice–wheat rotation system. The total energy input of the wet direct-seeded rice–wheat rotation system was greater than that of the dry direct-seeded and transplanted rice–wheat rotation systems. The current rice–wheat rotation production is highly dependent on non-renewable energy. Optimizing water and fertilizer management practices in rice and wheat production, improving water and fertilizer use efficiency is an effective way to reduce energy input in rice and wheat production.

The total energy output and net energy of the transplanted rice–wheat rotation system were slightly higher than those of the dry direct-seeded rice–wheat rotation system, but its energy production efficiency was lower than that of the dry direct-seeded rice–wheat rotation system. Therefore, from the perspective of energy output, the transplanted rice–wheat rotation system is a better method of rice–wheat rotation production and is suitable for promotion in rice–wheat rotation production areas with poor irrigation conditions. The dry direct-seeded rice–wheat rotation system has the highest energy production efficiency, which is a low energy consumption and high energy efficiency rice–wheat rotation production method, and is suitable for promotion in rice–wheat rotation production areas with poor irrigation conditions.

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CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

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