Human Energy Expenditure in Lowland Rice Cultivation in Malaysia

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ABSTRACT. *A study was undertaken to evaluate the human energy consumption of various field operations involved in lowland rice cultivation in Malaysia. Based on recorded average heart rates, fertilizing was found to be the most strenuous operation, with an average heart rate of 138 beats min^{-1}. There were no significant differences in the average heart rates of the subjects among the individual tasks within the first plowing, second plowing, and harvesting operations, with the average heart rates for these three tasks being 116, 106, and 106 beats min^{-1}, respectively. The corresponding energy expenditures were 3.90, 3.43, and 3.35 kcal min^{-1}. Loading the seed into the blower tank and broadcasting the seed were the most critical tasks for the seed broadcasting operation, with average heart rates of 124 and 136 beats min^{-1}, respectively. The highest energy expenditure of 418.38 kcal ha^{-1} was observed for seed broadcasting, and the lowest energy expenditure of 127.96 kcal ha^{-1} was for second plowing. The total seasonal human energy expenditure for rice cultivation was estimated to be 5810.71 kcal ha^{-1}, 55.7% of which was spent on pesticide spraying. Although the sample size in this study was relatively small, the results indicated that human energy expenditure per unit area (kcal ha^{-1}) was positively linked to the average heart rate of the subjects and negatively linked to the field capacity. Thus, mechanization of certain tasks could decrease worker physical effort and fatigue and increase production.*

Keywords. *Ergonomics, Field capacity, Field operations, Heart rate, Human energy expenditure, Mechanization, Rice cultivation.*

Rice is an important commodity and a main staple food in many Asian countries. In 2004, the area under rice cultivation in Malaysia was 667,310 ha, with a production of 2.2 Mt. Typically, Malaysia produces 75% of its national rice demand, with the balance mainly imported being from Thailand and Vietnam. As the population grows, pressure to plant more rice has increased. However, it is difficult for the country to increase its rice production, mainly because of a severe labor shortage in its agricultural sector. The primary contributing factors to the labor shortage are

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hard physical field work conditions and the likelihood of worker injury. Farm work often puts significant stress on agricultural workers. If this stress is excessive and goes on for some time, it can also lead to mental and physical ill health. For example, it was reported that chores such as the manual handling of farm machinery, lifting and carrying water and feed buckets, and repetitive use of hand tools (e.g., shovels, rakes) may increase the risk of developing one or more musculoskeletal disorders (MSDs) (Allread et al., 2004). Some agricultural activities also involve forceful exertions, stooping, static and awkward postures, and continual bending and twisting at the waist (Meyers et al., 1997).

In order to overcome the labor shortage and improve the working conditions of agricultural workers, a farm mechanization program in rice production is being introduced in Malaysia. The implementation of appropriate farm mechanization is also expected to increase crop yield and productivity (Baruah et al., 2004). Although many different farm machines are used for rice production in the world, there is no scientific recommendation to suit local farmers' need in Malaysia. Local recommendation is important because, as a developing country, Malaysia cannot afford to mechanize all farming activities involved in rice production. Therefore, before implementing a mechanization scheme, it is desirable to identify the agricultural tasks that are considered critical and strenuous for workers, so that those tasks can be prioritized for mechanical assistance. The identification of critical agricultural tasks or operations within the crop production activities is also essential to increase the effectiveness and efficiency of machine use. Inappropriate use of machinery may result in an unnecessary increase in production costs.

Critical agricultural tasks usually make workers tired because they are energy-intensive and consume much the workers' energy. A convenient and practical method for identifying critical tasks is measuring the human energy expenditures for the various field operations. Human energy expenditure is determined by a number of factors, including the intensity and duration of the activity, age, gender, body weight, and the surrounding environment (Westerterp, 2001). At present, systematic efforts to evaluate the human energy expenditure of various agricultural operations in rice cultivation are generally non-existent. Thus, measuring human energy expenditure in agricultural operations is essential for making practical recommendations of suitable methods and equipment for adoption in field operations. This should result in better equipment design, and improve the man-machine performance and the safety level on farms.

Curteon (1947) and Smolander et al. (2008) suggested that the most pertinent parameters for assessing human energy requirements for performing various types of operations were the basic metabolic rate, heart rate, and oxygen consumption of the workers. As measurements of basic metabolic rate and oxygen consumption under actual field conditions are scarce, energy expenditure is generally estimated from heart rate data after calibrating the subjects in a laboratory (Tiwari and Gite, 2002). Roscoe (1993) claimed that heart rate is the most useful parameter among the available physiological variables for assessing the workload of human subjects. Kroemer et al. (1997) showed that heart rate responded more quickly to changes in work demands and hence more readily indicated changes in body functions due to changes in the working environment. The heart rate variability (HRV) analysis has also been shown to be a simple, non-invasive technique that is capable of assessing autonomic heart rate (HR) modulation by means of instantaneous measurement of variations in the beat-to-beat intervals (Venderlei et al., 2008).

Nag et al. (1980) studied the workload of several agricultural operations and reported that the energy expenditure varied from 1.07 kcal min^{-1} for bird-scaring activity to 7.06 kcal min^{-1} for bund-trimming operations. Kathirvel et al. (1991) reported that the average energy expended by subjects for puddling with power tillers varied from 3.81 to 5.74 kcal min^{-1}. Mamansari et al. (1999), in undertaking an ergonomic evaluation of power tillers in Thailand, reported that the highest energy expenditure was in primary plowing, followed by secondary plowing, while the least was in harrowing. In terms of heart rate measurement, Nag and Datt (1979) found that the mean heart rate varied from 105 to 120 beats min^{-1} for weeding operations. They also showed that working posture (sitting or bending) caused little difference in the energy expenditure for weeding. Yadav and Srivastava (1984) observed that the human energy expenditure for sugarcane harvesting with knives ranged from 3.88 to 5.87 kcal min^{-1}. A model for predicting energy expenditure from two groups of physical data on body movement and type of work was proposed and tested by Aberg et al. (1967).

Currently, almost no data are available on the energy expenditure for the farming operations in lowland rice cultivation in Malaysia. Thus, the purpose of this article was to obtain necessary field data to assist the implementation of an appropriate mechanization plan, with its perceived benefits for worker safety and health and increased production efficiency. This was achieved by measuring the human energy expenditure and the heart rate of rice growers in completing various field operations in rice production. The field capacity and the duration of different tasks were also measured. Ultimately, this study will be extended to other crop production systems.

Measurement Methods

The field study was undertaken to evaluate the human energy consumption pattern of the various field operations involved in lowland rice cultivation in Malaysia. Pertinent information concerning the human energy expenditure pattern of the mechanized rice cultivation system was collected at three locations: Sawah Sempadan, Sungai Burong, and Sungai Besar of the Tanjong Karang Rice Irrigation Scheme in the Kuala Selangor and Sabak Bernam districts of Malaysia. The data collection exercise was carried out in the planting season during the months of October to January for six rice cultivation operations: first plowing, second plowing, seed planting and broadcasting, fertilizing, pesticide spraying, and harvesting. Each field operation may consist of several tasks. For example, the seed planting and broadcasting operation may consist of the following tasks: loading seed and fertilizer, lifting loads, broadcasting the seed, walking in the field, and distributing loads.

First and second plowing were carried out using a locally made 203 mm rotavator and a 282 mm rotavator, attached to a 41 kW Fiat 640 diesel engine tractor (fig. 1). Seed broadcasting was performed by direct seeding using a 3.5 hp (2.6 kW) knapsack-type powered broadcaster loaded with pregerminated rice seed of MR 219 variety (fig. 2). The total weight of the broadcaster and seed was 22 kg (10 kg for seed and 12 kg for the broadcaster). Applications of NPK fertilizers were undertaken at 15, 35, and 55 days after planting at an application rate of 200 kg ha^{-1}, in accordance with the Malaysia Department of Agriculture (DOA, 2002). Fertilizing operations were carried out using the same machine used for seed broadcasting. For controlling weeds, pre-emergence and post-emergence herbicides were applied using a knapsack mist blower

Figure 1. Straight driving of the tractor during second plowing.

Figure 2. Seed broadcasting with knapsack powered blower.

with a total weight of 29 kg, consisting of 12 kg for the mist blower and 17 kg for the pesticide solution (fig. 3). At crop maturity, the rice was harvested using a self-propelled, 82 kW combine harvester (model 1545, New Holland Clayson) with an effective cutting width of 4.57 m (fig. 4).

Figure 3. Spraying pesticide in a paddy field with knapsack powered blower.

Figure 4. Straight driving of the combine harvester.

A total of 16 experienced and healthy male rice growers were recruited as the subjects to perform the various field operations in this study. They represented the typical workforce for lowland rice cultivation in Malaysia. Prior to conducting the experiments, the subjects were familiarized with the experimental protocols so as to enlist

Table 1. Physical characteristics of the 16 male subjects.

Subject	Operation Involved	Age (years)	Weight (kg)	Height (cm)
1	First plowing	25	58	170
2	First plowing	19	57	167
3	First plowing	25	67	165
4	Second plowing	24	65	176
5	Second plowing	24	63	173
6	Seed broadcasting	50	65	170
7	Seed broadcasting	39	48	160
8	Pesticide spraying	44	57	158
9	Pesticide spraying	34	66	165
10	Pesticide spraying, fertilizing	25	64	175
11	Pesticide spraying	34	45	162
12	Fertilizing	20	55	160
13	Fertilizing	33	75	165
14	Harvesting	31	109	162
15	Harvesting	21	46	167
16	Harvesting	30	73	165
Mean		29.9	63.3	166.3
SD		8.8	15.0	5.4

their full cooperation. Each subject was also instructed to perform the given tasks as normal routine work. Before the commencement of each task, anthropometric data on the subjects involved in the particular field operation were recorded (table 1). All measurements for each of the six field operations were conducted between 8:30 a.m. and 12:00 noon to ensure consistency and uniformity in the measured data. The time taken to complete each task within each field operation under a known area of coverage was measured using a digital stopwatch.

For computation of the heart rate and human energy expenditure of the various field operations, the heart rate of the subjects performing the respective tasks involved in a field operation was continuously recorded using a Polar S810 heart rate monitor (Polar Electro, Kempele, Finland). The Polar S810, a relatively inexpensive tool, has been widely used to monitor the heart rates and in HRV analysis, especially in the medical and sports sciences (Nunan et al., 2008; Vanderlei et al., 2008). The Polar S810 was set to record at the sampling frequency of 1000 Hz, providing an accuracy of 1 ms (Gamelin et al., 2006). The Polar S810 consists of a cheststrap heart rate transmitter and a wristwatch receiver. The heart rate transmitter sends the heart beat signals via an electromagnetic field to the wristwatch receiver. All the collected data were analyzed in the laboratory. Polar Precision Performance software (Polar Electro, Kempele, Finland) was then used to analyze the heart rate data and convert it into energy expenditure. The energy expenditure assessment in this software is based on generalizable gender-specific regression equations including age, body weight, and heart rate developed for the assessment of energy expenditure during exercise for adults (Hiilloskorpi et al., 1999). The reference measure for the energy expenditure in the laboratory was gas analysis based on the Weir equation (Weir, 1949).

Analysis of variance (ANOVA) was performed to statistically determine the mean effect of field operations on the average heart rate and human energy expenditure. Following that, Duncan's multiple range test (DMRT) was used to statistically compare means of average heart rate and means of human energy expenditure between tasks within a specific field operation and between field operations. The percentage of the average time taken for completing each task within each field operation was also computed. Finally, stepwise multiple regression was conducted to establish the mathematical relationship of human energy expenditure with the recorded average heart rate and field capacity.

Results and Discussions

Percentage Distribution of Tasks Duration

Percentage of time distribution and average heart rate for each task involved within the field operations are given in tables 2 and 3, respectively. About 65.1% and 62.3% of the time spent on first and second plowing, respectively, was accounted for with straight driving of the tractor. Straight driving of the combine harvester also took 56.2% of the total harvesting time. Results from ANOVA indicated that there were no significant differences in the average heart rates of the subjects among the individual tasks within the first plowing, second plowing, and harvesting operations (table 3). This implied that all the tasks within each of these operations were approximately of equal physical effort across the subjects.

Table 2. Percentage distribution of task duration for the six field operations.[a]

	Proportion of Time (%)					
Task	First Plowing	Second Plowing	Seed Broadcast	Fertilizing	Pesticide Spraying	Harvesting
Straight driving	65.1 a	62.3 a	--	--	--	56.2 a
Cornering	35.1 b	37.6 b	--	--	--	31.7 b
Loading seed/fertilizer	--	--	20.3 b	18.6 b	--	--
Lifting load	--	--	19.2 b	11.1 c	8.5 d	--
Broadcasting seed	--	--	42.1 a	--	--	--
Walking in the field	--	--	8.2 c	17.8 b	18.1 c	--
Distributing load	--	--	10.2 c	17.6 b	--	--
Spreading fertilizer	--	--	--	35.0 a	--	--
Mixing pesticide	--	--	--	--	31.0 b	--
Spraying pesticide	--	--	--	--	42.4 a	--
Offloading grain	--	--	--	--	--	12.3 c
Total	100	100	100	100	100	100

[a] Values followed by the same letters are not statistically different at the 0.05 level of significance.

Table 3. Comparison of average heart rates of subjects for tasks within the six field operations.[a]

	Average Heart Rate (beats min^{-1})					
Task	First Plowing	Second Plowing	Seed Broadcast	Fertilizing	Pesticide Spraying	Harvesting
Straight driving	116 a	106 a	--	--	--	105 a
Cornering	115 a	105 a	--	--	--	109 a
Loading seed/fertilizer	--	--	124 a	135 ab	--	--
Lifting load	--	--	123 a	135 ab	129 ab	--
Broadcasting seed	--	--	124 a	--	--	--
Walking in the field	--	--	116 a	135 ab	134 b	--
Distributing load	--	--	117 a	129 b	--	--
Spreading fertilizer	--	--	--	145 a	--	--
Mixing pesticide	--	--	--	--	117 b	--
Spraying pesticide	--	--	--	--	141 a	--
Offloading grain	--	--	--	--	--	103 a

[a] Values followed by the same letters are not statistically different at the 0.05 level of significance.

For the seed broadcasting operation, the highest time percentage (42.1%) was spent on broadcasting the seed on the plowed land, followed by loading seed into the blower tank, which accounted for 20.3% of the total time. Among the fertilizer application tasks, spreading the fertilizer consumed about 35.0% of the total fertilizing time. Spraying pesticides for weed and pest control took 42.4% of the total spraying time. The ANOVA performed also showed that there were no significant differences in average heart rates among the various tasks for the seed broadcasting operation, with the highest average rates of 124 beats min^{-1} observed for the tasks of loading the seed into the blower tank and broadcasting the seed (table 3), which represent the critical tasks for this operation.

Although the tasks of spreading fertilizer and spraying pesticide recorded the highest heart rates of the subjects, they were not significantly different from the heart rates for the other tasks within the fertilizing and pesticide spraying operations. On the basis of the average heart rates, the most critical tasks within the spraying operation are walking in the field and spraying pesticide (141 beats min^{-1}), while spreading fertilizer represents the most critical task within the fertilizing operation (145 beats min^{-1}).

Average Heart Rate, Energy Expenditure, and Field Capacity

Comparisons of average heart rate, energy expenditure, and field capacity of the six field operations are given in table 4. The highest heart rate of 138 beats min^{-1} was observed for the fertilizing, which was 30.2% higher than the lowest heart rate of 106 beats min^{-1} observed for second plowing. The average heart rate for fertilizing was, however, not significantly different from the average heart rate for pesticide spraying, but significantly different from that of the other field operations. Sandhar (1979) reported that the average heart rate for operating a knapsack sprayer ranged from 103.4 to 128.8 beats min^{-1}, which was lower than the value found in this study for pesticide spraying (130 beats min^{-1}).

Overall, the energy consumption for all the field operations (table 4) was much higher than the energy consumption for domestic activities, which ranged from 1.95 to 2.87 kcal min^{-1}, as reported by Saraswathy et al. (1987). The energy expenditure for the first plowing operation in this study was found to be at least 44% lower than the amount reported by Nwuba and Kaul (1986) for a tillage operation using a traditional short-handled hoe, which ranged from 7.00 to 9.50 kcal min^{-1}. This clearly demonstrated the advantage of using machinery for field operations in order to reduce human energy expenditure, thereby likely reducing worker fatigue, too. For the seeding operation, it was found the broadcasting method used in this study consumed more energy than the manual transplanter method, which only consumed 3.09 kcal min^{-1} (Baqui and Latin, 1982).

Table 4. Average heart rate, energy expenditure, and field capacity for the field operations.[a]

Field Operation	Average Heart Rate (beats min^{-1})	Field Capacity (ha h^{-1})	Energy Expenditure (kcal min^{-1})	Energy Expenditure (kcal ha^{-1})
First plowing	116 cd	1.16 b	3.90 b	201.60 b
Second plowing	106 d	1.61 a	3.43 b	127.96 bc
Seed broadcasting	122 bc	0.96 c	6.69 a	418.38 a
Fertilizing	138 a	0.94 c	5.54 a	353.71 a
Pesticide spraying	130 ab	0.75 d	5.06 a	404.79 a
Harvesting	106 d	0.49 e	3.35 b	409.61 a

[a] Values followed by the same letters are not statistically different at the 0.05 level of significance.

Table 5. Percentage distribution of human energy expenditure of field operations.

Field Operation	Number of Operations Performed per Season	Human Energy Expenditure per Operation (kcal ha^{-1})	Total Seasonal Human Energy Expenditure (kcal ha^{-1})	Percentage of Seasonal Energy Expenditure (%)
First plowing	1	201.60	201.60	3.5
Second plowing	1	127.96	127.96	2.2
Seed broadcasting	1	418.38	418.38	7.2
Fertilizing	4	353.7	1414.84	24.4
Pesticide spraying	8	404.79	3238.32	55.7
Harvesting	1	409.61	409.61	7.0
Total		1916.05	5810.71	100.0

The highest energy expenditure of 418.38 kcal ha^{-1} was observed for the seed broadcasting operation (table 4), which was 227% higher than the lowest energy expenditure of 127.96 kcal ha^{-1} observed for the second plowing operation. The energy expenditure for seed broadcasting was, however, not significantly different from the energy expenditures for the fertilizing, pesticide spraying and harvesting operations, but significantly different from first and second plowing operations.

The highest field capacity of 1.61 ha h^{-1} was observed for second plowing, which was 229% higher than the lowest field capacity of 0.49 ha h^{-1} observed for harvesting. Overall, the human energy expenditure was very significantly affected by the working nature of the individual operation. Generally, a low field capacity operation corresponded to a high energy expenditure for the subjects.

Seasonal Comparison of Human Energy Expenditure of Field Operations

The total seasonal human energy expenditure for rice cultivation for a typical farmer at the Tanjong Karang Rice Scheme in Malaysia was found to be 5810.71 kcal ha^{-1} (table 5). Among the different field operations undertaken, the highest seasonal human energy expenditure in the rice cultivation process was observed for pesticide spraying (3238.32 kcal ha^{-1}), which took about 55.7% of the total human energy expenditure in the season. Second plowing consumed the least amount of human energy in the season (127.96 kcal ha^{-1}). Greater energy expenditure was observed for spraying as the result of several applications of pesticide due to severe weed and pest infestation during the cropping season.

Relationship of Energy Expenditure, Heart Rate, and Field Capacity

The variables considered initially for the regression analysis were initial heart rate (IHR), average heart rate (AHR), difference between initial and average heart rates (DIFHR), duration of field operation (DOP), field capacity (FC), and energy expenditure per unit area (EEA). Coefficients were calculated in order to determine the extent to which these variables are correlated to each other and to what extent field operation decisions could be predicted based on such correlations (table 6).

Table 6. Correlation matrix for heart rate variables, field capacity and energy expenditure.[a]

Parameter	1	2	3	4	5	6
1. Initial heart rate (IHR)	1.00	--	--	--	--	--
2. Average heart rate (AHR)	0.86**	1.00	--	--	--	--
3. Difference between IHR and AHR (DIFHR)	0.40*	0.81**	1.00	--	--	--
4. Duration of field operation (DOP)	-0.26	-0.31	-0.26	1.00	--	--
5. Field capacity (FC)	0.08	-0.07	-0.22	-0.45**	1.00	--
6. Energy expenditure per unit area (EEA)	0.47**	0.66**	0.65**	0.01	-0.49**	1.00

[a] Asterisks indicate that the correlation is significant at the 0.05 (*) or 0.01 (**) probability level.

From table 6, it can be seen that the heart rate variables IHR, AHR, and DIFHR were significantly correlated with each other. Average heart rate (AHR) was therefore selected for inclusion in the regression equation because it had the highest correlation coefficient with energy expenditure ($r = 0.66$). Field capacity was also chosen for inclusion in the regression equation because it was significantly correlated with both the duration of field operation ($r = -0.45$) and energy expenditure ($r = -0.49$). Based on these results, the following relationship between energy expenditure per unit area, average heart rate, and field capacity was derived:

$$EEA = -151.74 + (5.61 \times AHR) - (217.95 \times FC) \quad (R^2 = 0.64) \qquad (1)$$

where EEA is the energy expenditure per unit area (kcal ha^{-1}), AHR is the average heart rate of the subjects (beats min^{-1}), and FC is the field capacity (ha h^{-1}). Overall, AHR contributed positively while FC contributed negatively to EEA.

Conclusion

A pilot study was undertaken to evaluate the human energy consumption and field capacity of various field operations involved in lowland rice cultivation in Malaysia in order to identify the agricultural tasks that are considered critical and strenuous for farm workers or of low productivity, so they can be prioritized for mechanization.

Based on the field measurement results, it was found that straight driving of the tractor or combine accounted for the highest proportion of time spent on the first plowing, second plowing, and harvesting operations. In the spraying and fertilizing operations, spreading fertilizer and spraying pesticide accounted for the highest proportions of time spent. The most critical field tasks in the rice production system in Malaysia were spreading fertilizer and spraying pesticide, with average heart rates of 138 and 130 beats min^{-1}, respectively. The highest field capacity (1.61 ha h^{-1}) was recorded for second plowing, while the lowest (0.49 ha h^{-1}) was recorded for harvesting. The total seasonal human energy expenditure for lowland rice cultivation was estimated to be 5810.71 kcal ha^{-1}, 55.7% of which was spent on pesticide spraying. Although the sample size in this study was small, the results indicate that the human energy expenditure per unit area (kcal ha^{-1}) was positively linked to the average heart rate of the subjects and negatively linked to the field capacity.

This study demonstrated that using farm machinery for field operations significantly saved human energy expenditure. Since no subject completed more than one task in this study, it was not possible to know whether the differences between subjects were significant. In the future, additional research should be carried out with an increased sample size and measured parameters. It is recommended that when designing new machines or improving current machines, greater focus should be given to the critical field operations that have the highest human energy expenditures and to the critical tasks within field operations that show the highest average heart rate. For this study, these were identified as spreading fertilizer and spraying pesticide.

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