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# Ergonomics evaluation of manually operated wheel sprayer

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**ABSTRACT**

Spraying is one of the most significant procedures in crop production because it protects crops from pests and diseases. Ergonomic intervention in spraying operations can give a solid foundation for recommendations on operating methods and efficient operation for increased production and safety. The ergonomic assessment of the manually operated wheel sprayer was based on heart rate, oxygen consumption rate, energy expenditure rate, and overall discomfort rating. Physiological workload increased proportionally with both variables, heart rate peaked at 118 beats $min^{-1}$, while oxygen consumption rate increases from 551 ml $min^{-1}$ to 665 ml $min^{-1}$ across the tested ranges (2.16-2.71 km $h^{-1}$ and 25-35 years). Similarly, the energy expenditure rate increased from 17.5 to 21.66 kJ $min^{-1}$. The overall discomfort rating followed this trend, reaching its maximum at a speed of 2.71 km $h^{-1}$ and an operator age of 35 years, suggesting that higher speeds and higher age of the operator significantly intensify the physical demands of the task. Average theoretical field capacity, actual field capacity, and field efficiency values of 0.44 ha $h^{-1}$, 0.32 ha $h^{-1}$, and 73%, respectively.

**KEYWORDS**

Ergonomics, Design Expert, Wheel Sprayer, Hear Rate, Overall Discomfort Rating

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Chilli (*Capsicum spp*.) is a high-value warm-season crop grown for its pungent fruits, which are high in capsaicin, vitamins, and antioxidants. It grows in well-drained, fertile loamy soils with a pH of 6.0-7.0 (Bosland and Votava, 2012) and prefers a warm, frost-free climate (20-30°C) with moderate rainfall, often demanding irrigation in dry areas. The crop is normally seeded using nursery-raised seedlings transplanted at 45-60 days of age, with spacing varies by variety (30-60 cm between rows, 30-45 cm between plants) (Sahoo *et al.,* 2015). Traditional agricultural spraying methods confront considerable issues, such as unequal application of pesticides, insecticides, and herbicides, which can harm crops, human health, and the environment. Integrating current technologies, on the other hand, can optimize chemical utilization (Wu *et al.* 2025; Gong *et al.* 2024). Implementing best practices can improve productivity and efficiency in agricultural production systems (Yang *et al.*, 2011). Human is the most vital component of human - animal - machine system in case of manually operated machines. While designing the agricultural implement, human energy requirement should be considered and care should be taken to eliminate or reduce operators walking behind thve implements.

Design of farm implements, with this consideration, can reduce the energy requirement on the implement without affecting its performance even in varied soil conditions. The issues related to the ergonomics such as anthropometric dimensions, strength parameters, and force required to operate the machine, level of comfort, should be understood and applied while designing the farm equipment. The goal of ergonomics is to design the task so that its power/force demand to operate the machine remains within the capabilities of workers. Plant protection is crucial for increasing crop yields since agricultural pests inflict significant damage and impede productivity. To limit these losses and maximize the advantages of other agricultural inputs, effective plant protection measures are required. Pesticides and liquid fertilizers are applied in agriculture using a variety of spraying technologies, which can be broadly classified as hand-operated, engine-operated, and tractor-operated sprayers and dusters. Conventional manual knapsack sprayers, while portable, place significant ergonomic strain on the user. This is due to the repetitive motion required for pumping and the weight of the liquid load carried on the back, which causes musculoskeletal stress in the back, shoulders, and arms (Matthews, 2018; Singh *et al.,* 2020). To address these operational challenges and improve ergonomics, manually operated wheel sprayer has been developed.

**Materials and Methods**

The existing knapsack sprayer was converted into a wheel sprayer with six nozzles, an expanded boom, and a second pressure unit attachment as a functioning and experimental unit. Machine components were designed using operational principles, tested, and compared to the usual approach to produce a correct shape in the form of a prototype. The mechanical design features were also given appropriate attention in order to provide adequate functional rigidity for the machine. The created manually operated wheel sprayer is made up of a frame, tank, boom, nozzle, pressure unit, nuts and bolts, ground wheel, and chain drive (fig 1). The ANOVA was used to determine the individual interaction of all independent parameters at 5% significance level and a 95% confidence level. The optimization of the ergonomics parameters was done using RSM of the design expert software.

The optimum values were determined by using the desirability functions and the solution with the desirable value was taken as optimum.

**Fig 1. Developed Wheel Sprayer**

**Heart Rate (HR)**

During the spraying operation, operator' heart rates were continuously monitored using a fingertip pulse oximeter (fig 2), with measurements recorded at 5-minute intervals to capture physiological responses accurately.

**Fig 2. Measuring heart rate**

**Table 1. Experimental design for ergonomics parameters**

| S. N. | Independent Variables | Levels | Details | Dependent Variables |
|---|---|---|---|---|
| 1 | Speed of the operator (Km $h^{-1}$) | 3 | 2.16, 2.64, 2.71 | Heart rate (HR), beats $min^{-1}$ |
| 2 | Age of the operator (Year) | 3 | 25, 30, 35 | Oxygen consumption rate (OCR), ml $min^{-1}$ |
| | | | | Energy expenditure rate (EER), kj $min^{-1}$ |
| | | | | Overall discomfort rating (ODR) a) |

### Oxygen Consumption Rate (OCR)

Oxygen consumption rate is a measured to access whole body fatigue. However, it was computed from the heart rate (HR) values of the operator by using the equation 1 given by (Singh *et al.,* 2008).

$$OCR = 0.0114\,HR - 0.68 \qquad (1)$$

Where,
OCR = Oxygen consumption, l $min^{-1}$
HR = Heart rate, beats $min^{-1}$

### Energy Expenditure Rate (EER)

Energy expenditure rate of the operator was calculated by using equation 2 (Yadav *et al.,* 2007).

$$EER = \frac{HR-66}{2.4} \qquad (2)$$

Where,
EER = Energy expenditure rate, kj $min^{-1}$

### Overall Discomfort Rating (ODR)

Discomfort is the body pain or fatigue arising as a result of working posture and excessive stress on muscles due to various physical activities performed by the subjects. For the assessment of ODR, a category ratio scale given by (Borg, 1982) was used (fig 3).

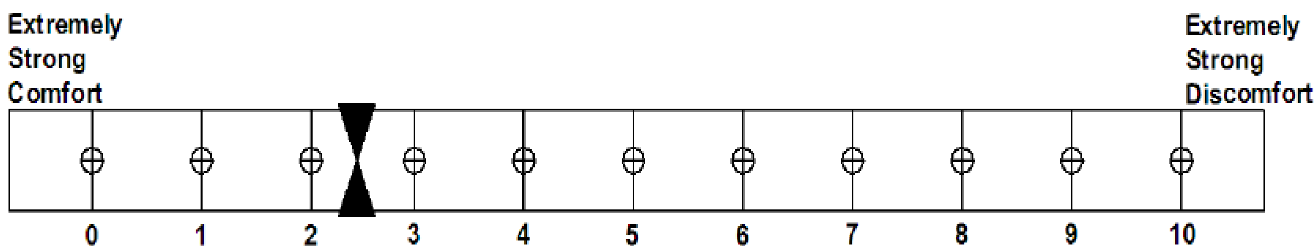


**Fig 3. Overall discomfort rating scale**

### Results and Discussion

To design the experiment and analysis of data, the ANOVA and design expert experimental design analysis were applied to evaluate the effect of treatments (also called control factors or fixed factors) [speed of the operator (A) and age of the operator (B)] on responses namely, heart rate, oxygen consumption rate, energy expenditure rate and overall discomfort rate respectively.

### Analysis of Variance

Analysis of variance (ANOVA) was used to determine the individual interaction of the entire control factor in the test. In this study, ANOVA was used to analyze the effect of independent variables on dependent variables 5% significant level and a 95% confidence level and the results are summarized in table 3 to 6.

According to table 3, the effects of speed of the operator and age of the operator on heart rate were significant at 5% significant level. Thus, the most important factor affecting the heart rate was age of the operator. According to table 4, the effects of speed of the operator and age of the operator on oxygen consumption rate were significant at 5% significant level. Thus, the most important factor affecting the oxygen consumption rate was age of the operator. Regarding to table 5, the effects of speed of the operator and age of the operator on energy expenditure rate were significant at 5% significant level. Thus, the most important factor affecting the energy expenditure rate was age of the operator. Regarding to table 6, the effects of speed of the operator and age of the operator on overall discomfort rating were significant at 5% significant level. Thus, the most important factor affecting the overall discomfort rating was age of the operator.

**Table 2. Optimization parameters for ergonomics**

| S. N. | Factors | | Mean Response | | | |
|---|---|---|---|---|---|---|
| | A (Km $h^{-1}$) | B (Year) | Heart Rate (Beats $min^{-1}$) | Oxygen Consumption Rate (ml $min^{-1}$) | Energy Expenditure Rate (kj $min^{-1}$) | Overall Discomfort Rating |
| 1 | 2.71 | 25 | 112 | 596 | 19.16 | 3 |
| 2 | 2.64 | 35 | 118 | 665 | 21.66 | 4 |
| 3 | 2.16 | 25 | 108 | 551 | 17.5 | 2 |
| 4 | 2.64 | 30 | 112 | 596 | 19.16 | 3 |
| 5 | 2.71 | 35 | 114 | 619 | 20 | 4 |
| 6 | 2.64 | 30 | 113 | 608 | 19.58 | 3 |
| 7 | 2.64 | 30 | 113 | 608 | 19.58 | 3 |
| 8 | 2.16 | 30 | 110 | 574 | 18.33 | 2 |
| 9 | 2.16 | 35 | 113 | 608 | 19.58 | 3 |
| 10 | 2.64 | 30 | 112 | 596 | 19.16 | 3 |
| 11 | 2.64 | 30 | 112 | 596 | 19.16 | 3 |
| 12 | 2.71 | 30 | 111 | 585 | 18.75 | 4 |
| 13 | 2.64 | 25 | 110 | 574 | 18.33 | 2 |

**Table 3. ANOVA for heart rate**

| Sources | Sum of Squares | df | Mean Square | F-value | P-value |
|---|---|---|---|---|---|
| Speed of the operator, km $h^{-1}$ (A) | 12 | 1 | 12 | 6.59 | 0.0280 |
| Age of the operator, Year (B) | 37.50 | 1 | 37.50 | 20.61 | 0.0011 |
| Residual error | 18.20 | 10 | 1.82 | | |

**Note:** Significant at 5% level of significance, P<0.05 Determine significance of factor at 95% of confidence level

**Table 4. ANOVA for oxygen consumption rate**

| Sources | Sum of Squares | df | Mean Square | F-value | P-value |
|---|---|---|---|---|---|
| Speed of the operator, km $h^{-1}$ (A) | 1515.40 | 1 | 1515.40 | 6.35 | 0.0304 |
| Age of the operator, Year (B) | 4873.50 | 1 | 4873.50 | 20.42 | 0.0011 |
| Residual error | 2386.79 | 10 | 238.68 | | |

**Table 5. ANOVA for energy expenditure rate**

| Sources | Sum of Squares | df | Mean Square | F-value | P-value |
|---|---|---|---|---|---|
| Speed of the operator, km $h^{-1}$ (A) | 2.08 | 1 | 2.08 | 6.60 | 0.0279 |
| Age of the operator, Year (B) | 6.51 | 1 | 6.51 | 20.72 | 0.0011 |
| Residual error | 3.14 | 10 | 0.3143 | | |

**Table 6. ANOVA for overall discomfort rating**

| Sources | Sum of Squares | df | Mean Square | F-value | P-value |
|---|---|---|---|---|---|
| Speed of the operator, km $h^{-1}$ (A) | 2.05 | 1 | 2.05 | 16.02 | 0.0025 |
| Age of the operator, Year (B) | 2.67 | 1 | 2.67 | 20.82 | 0.0010 |
| Residual error | 1.28 | 10 | 0.2135 | | |

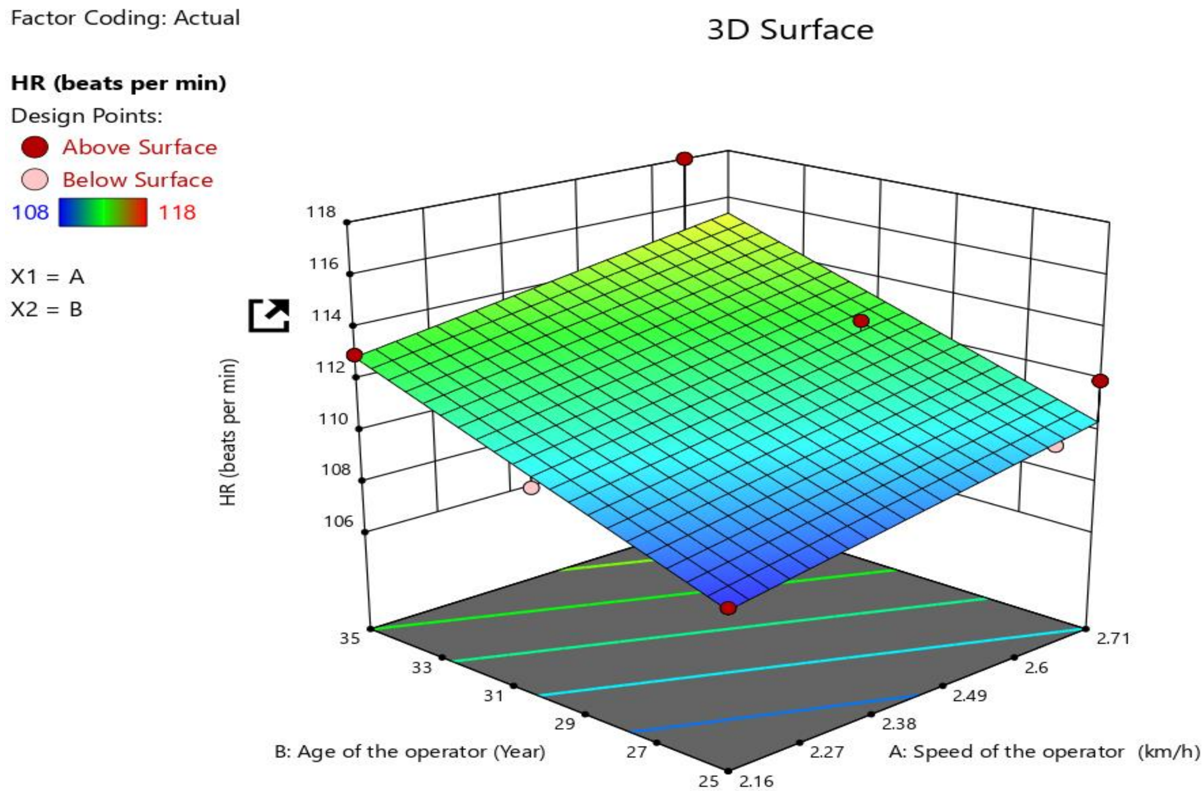


**Fig 4. Effect of different factors on heart rate**

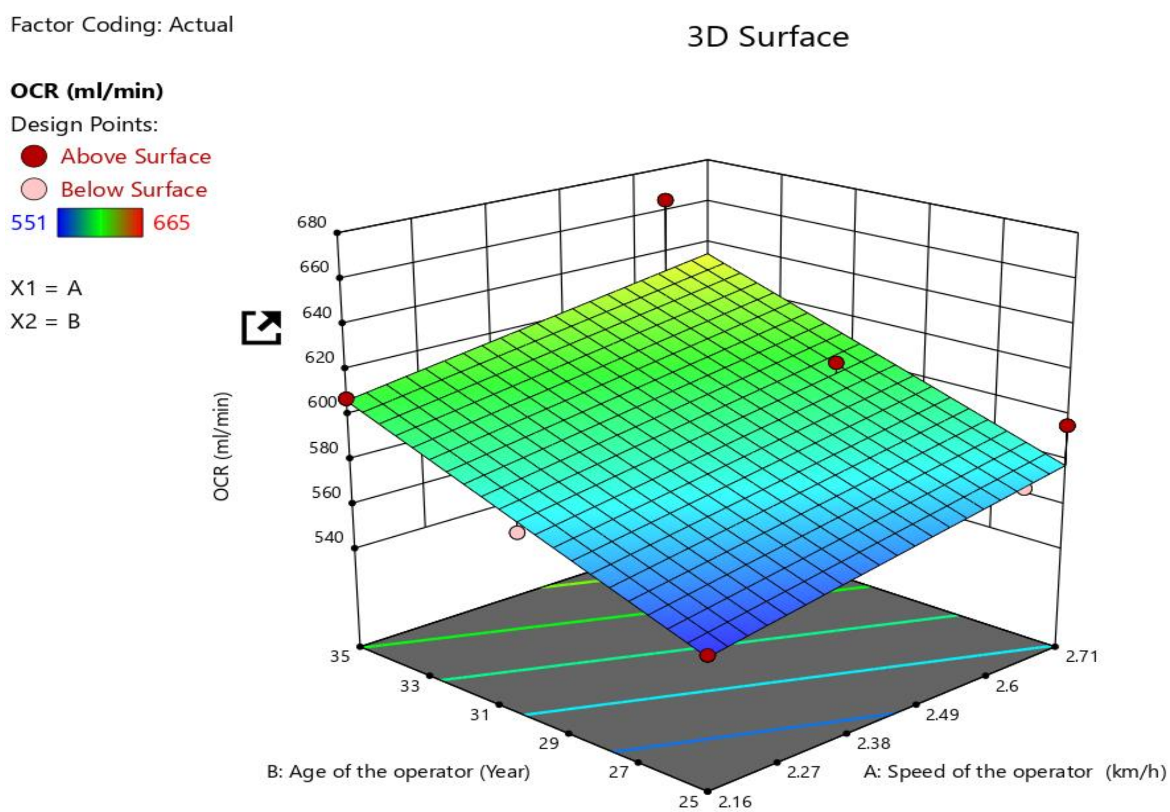


**Fig 5. Effect of different factors on oxygen consumption rate**

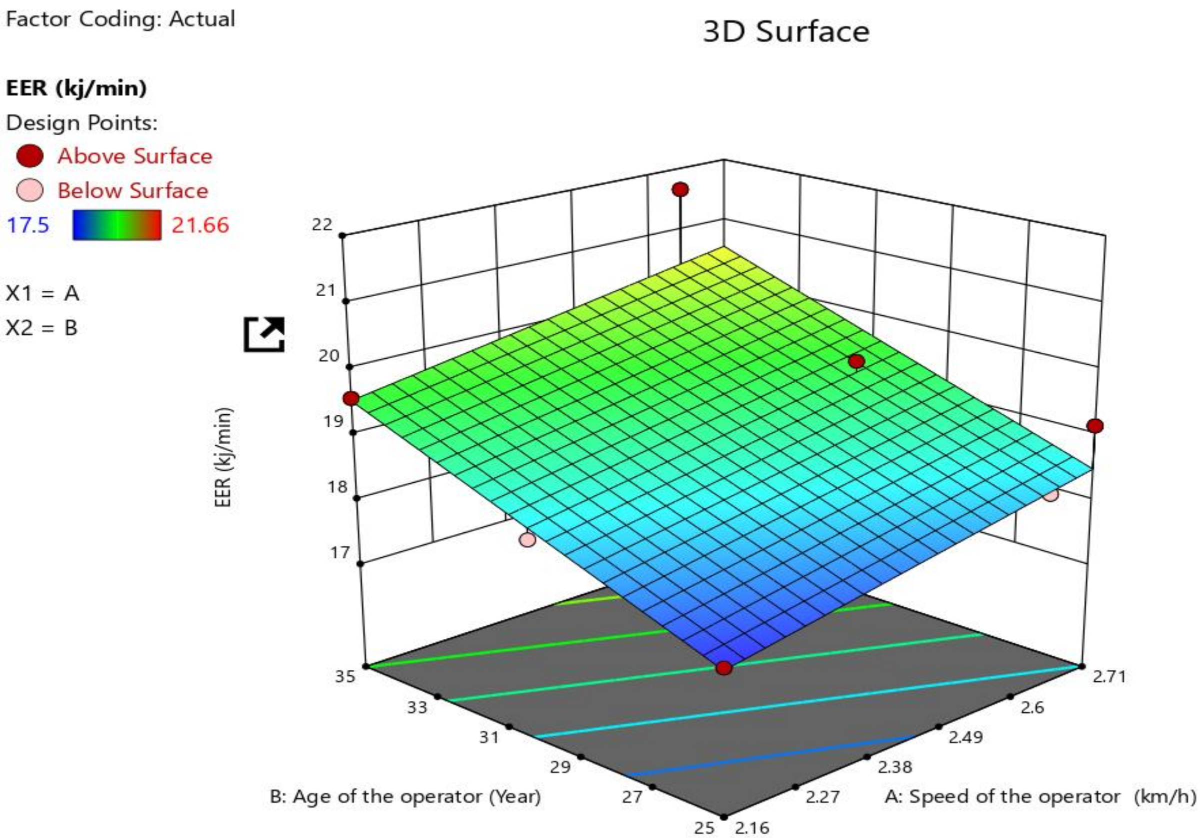


**Fig 6. Effect of different factors on energy expenditure rate**

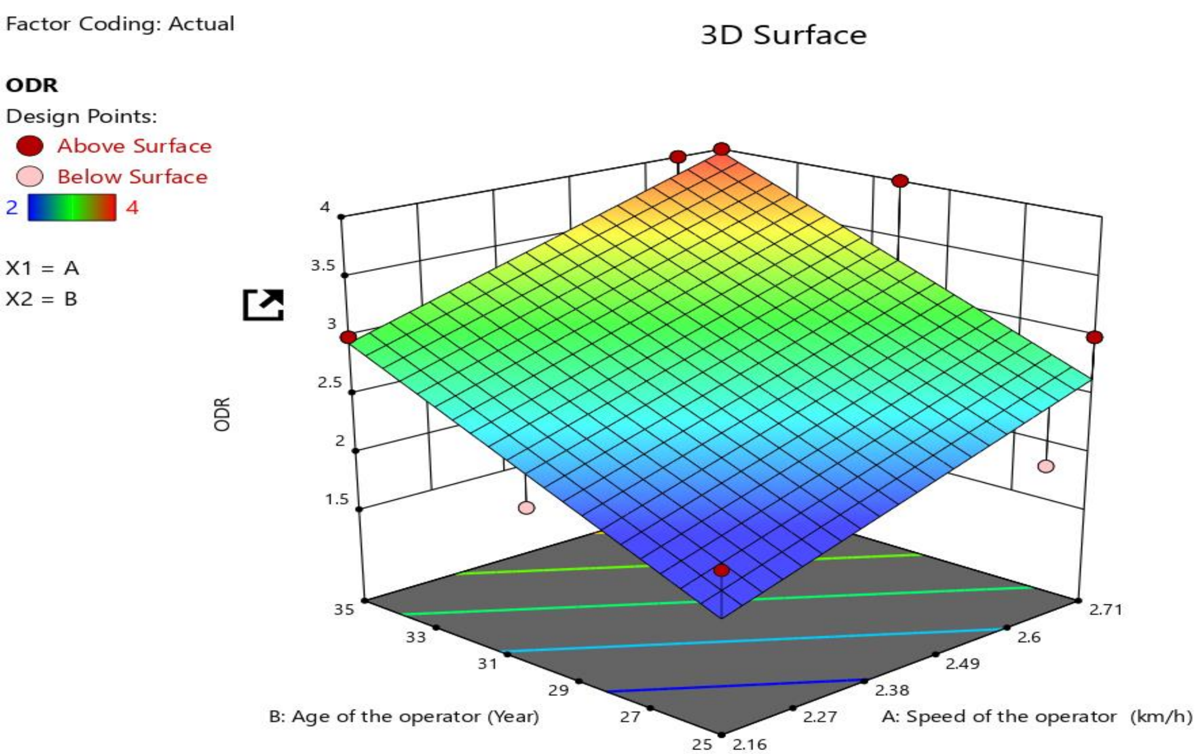


**Fig 7. Effect of different factors on overall discomfort rating**

**Analysis of the Operating Parameters for Heart Rate (HR)**

The combined effect of speed of the operator and age of the opertor on heart rate (HR). The vertical Z axis measures HR in beats per minute, showing a clear upward trend as both speed and age increase (fig 4). This relationship is represented by the colored surface, which transitions from blue (lower HR) at lower speeds and younger ages to yellow-green (higher HR) as both factors rise. The red and pink dots represent actual experimental data points relative to the predicted model, indicating whether specific measurements were above or below the projected surface. Overall, the graph demonstrates that physical exertion (speed of the operator) and demographic factors (age of the operator) have a direct, additive impact on heart rate. The graph shows that the lowest heart rate of approximately 108 beats $min^{-1}$ occurs at the minimum values a 25 year old operator moving at 2.16 km $h^{-1}$. Conversely, the heart rate increases to its peak of nearly 118 beats $min^{-1}$ when a 35 year old operator reaches the maximum speed of 2.71 km $h^{-1}$.

**Analysis of the Operating Parameters for Oxygen Consumption Rate (OCR)**

The relationship between speed of the operator and age of the operator regarding the response variable OCR, measured in ml $min^{-1}$ (fig 5). The response scale on the vertical Z-axis ranges from a minimum of 540 ml $min^{-1}$ to a maximum of 680 ml $min^{-1}$. The horizontal X-axis represents the speed of the operator, ranging from 2.16 to 2.71 km $h^{-1}$, while the Y-axis represents the age of the operator, ranging from 25 to 35 years. The color-coded surface identifies the predicted output, where blue represents the lowest values around 551 ml $min^{-1}$ and red/orange represents the highest values reaching 665 ml $min^{-1}$**.** The graph indicates a steady upward trend in OCR as both factors increase. Specifically, the lowest OCR values occur when speed is at 2.16 km $h^{-1}$ and age is at 25 years**.**

**Analysis of the Operating Parameters for Energy Expenditure Rate (EER)**

The relationship between speed of the operator and age of the operator regarding the response variable EER, measured in kj $min^{-1}$ (fig 6).

The variation in Energy Expenditure Rate (EER)**,** which ranges from 17 to 22 kj $min^{-1}$, as a function of the operator's speed and age. The base of the model shows that at a minimum speed of 2.16 km $h^{-1}$ and an age of 25 years, the predicted EER is at its lowest point of 17.5 kj $min^{-1}$, represented by the dark blue area of the surface. As both factors increase, there is a steady rise in energy expenditure; specifically, when the speed reaches 2.71 km $h^{-1}$ and the operator's age is 35 years, the EER increases to a peak value of 21.66 kj $min^{-1}$, indicated by the yellow-green transition on the surface. The plot also includes specific design points to show the model's accuracy, where red dots signify actual experimental values measured above the predicted surface and light pink circles represent those recorded below it across the various speed increments of 2.27, 2.38, 2.49, and 2.6 km $h^{-1}$.

**Analysis of the Operating Parameters for Overall Discomfort Rating (ODR)**

The relationship between a response variable called (ODR**)** and two independent factors**,** (speed of the operator) and (age of the operator) (fig 7). The vertical z-axis measures the ODR value, which ranges from 1.5 to 4, while the horizontal axes show speed (2.16 to 2.71 km $h^{-1}$) and age (25 to 35 years). The colored surface represents the predicted model, where the color gradient moving from blue at the low end to warm orange/red at the high end indicates that ODR increases as both speed and age increase.

**Conclusion**

Based on the study undertaken, following conclusions can be drawn. The average values of theoretical field capacity, actual field capacity and field efficiency were observed, 0.44 ha $h^{-1}$, 0.32 ha $h^{-1}$ and 73 % respectively. The results of ANOVA showed that speed of the operator and age of the operator are the significant parameters. The analysis reveals that heart rate increase positively with age and speed of the operator, reaching a maximum of 118 beats $min^{-1}$ for 35 year-old operators at 2.71 km $h^{-1}$. Oxygen consumption rate increases proportionally with both operator speed and age of the operator. OCR increases from a minimum of 551 ml $min^{-1}$ at 2.16 km $h^{-1}$ and 25 years to a peak of 665 ml $min^{-1}$ at 2.71 km $h^{-1}$ and 35 years.

Energy expenditure rate increases proportionally with both operating speed and operator age, rising from 17.5 to 21.66 kj $min^{-1}$. The ODR value is directly proportional to both operator speed and age, with the highest response occurring at the maximum tested parameters of 2.71 km $h^{-1}$ and 35 years.

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