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Design of a Rotary Table Hydroponic System for Agricultural Improvement in Limited Urban Land

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Abstract

This research focuses on the design of a rotary table hydroponic device for effective, efficient, and space-saving plant growth. With machine dimensions of 1570 x 600 x 2360 mm, a frame made of 2 mm thick 30 x 30 mm galvanized hollow steel, and a 1.5 HP electric motor, the machine is engineered to maximize land utilization in hydroponic methods. Stress analysis on the frame reveals maximum and minimum values of 3,631e+01 MPa and 2,064e-03 MPa, respectively, while the safety factor reaches 1,211e+05 and 6,886e+00, surpassing the safety factor range for static loads. The results of this experiment confirm the effectiveness and safety of the design, demonstrating that this rotary table hydroponic device can be optimally utilized in hydroponic plant cultivation.

Keywords: Hidroponics, rotary table, electric motor, frame strength

INTRODUCTION

Hydroponics is a cultivation technique that has become increasingly popular recently, especially in urban areas with limited land. The hydroponic method allows plants to grow in nutrient-rich water [1]. One of the hydroponic methods that can be utilized is the rotary table system. This system is an innovation that enables vertical plant cultivation by utilizing limited space. In the rotary table system, plants are grown in a container located on a rotating table. During the table's rotation, plants receive the necessary nutrients from the nutrient solution beneath the container. The hydroponic rotary table system is capable of increasing plant production up to 20 times more than traditional methods [2]. Additionally, it offers advantages in water and nutrient efficiency, making it suitable for areas with water constraints. In the context of limited urban space, the hydroponic rotary table system can be a solution to enhance agricultural productivity. By utilizing confined spaces, this system can generate higher yields, thereby aiding households and home industries in their development. Through the development of a smaller and space-efficient hydroponic rotary table device, Muflihah successfully cultivated various crops such as lettuce, spinach, and pakchoi with satisfactory harvest results [3].

Hydroponics enables farming in challenging locations, such as urban or less fertile areas. A suitable solution to address limited land issues is the design of the double rotary table hydroponic device, which can assist communities in improving agricultural yields by cultivating vegetables. This not only aids homemakers in being more productive but also benefits home and large-scale industries due to the increasing food demands with a growing population [4]. This research aims to design an effective, efficient, and space-saving double rotary table hydroponic device.

RESEARCH METHODS

The aim of this research method is to create the design of a double rotary table hydroponic system for limited land. The steps taken in designing this double rotary table hydroponic system involve several stages. Firstly, the researcher conducts a literature review to understand the basic principles of hydroponics and the operation principles of the rotary table. Hydroponics is a cultivation method that does not use soil as a growing medium. Instead, plants grow in a nutrient solution rich in essential elements. The schematic design of the hydroponic apparatus designed can be seen in **Fig. 1**.

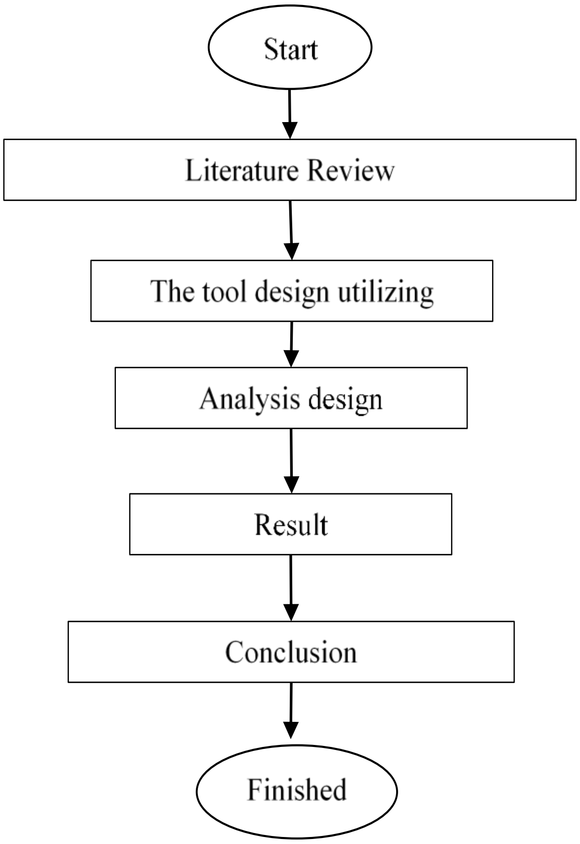


Fig. 1. Research flow diagram schematic

1. Literature Review
   Literature review in the context of hydroponics involves research and exploration of literature, scientific publications, books, articles, and other information sources related to the fundamental principles, techniques, technologies, and recent developments in hydroponic systems. The purpose of this literature review is to comprehend and gather knowledge existing in the hydroponic domain, including utilized methods, encountered challenges, recent innovations, and relevant research findings.
2. Design of a Double Rotary Table Hydroponic Device using Auto-CAD
   Designing hydroponic schematics can be accomplished using graphic design software such as Auto-CAD, determining dimensions and scale, specifying the structure's design, and identifying the components to be employed in the double rotary table hydroponic device.
3. Analysis of the Design of the Double Rotary Table Hydroponic System
   The analysis of the double rotary table hydroponic design involves the evaluation and assessment of various design aspects to ensure the system is effective, efficient, and aligns with the intended objectives.

4. Results

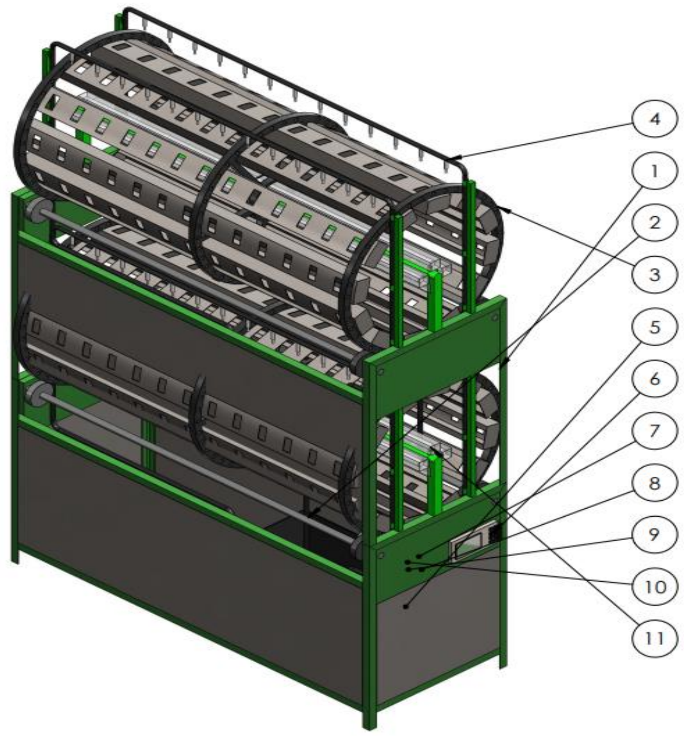
   The outcomes of the hydroponic design may vary depending on the goals, scale, and application context. The following are potential positive results that can be achieved through the implementation of the double rotary table hydroponic design.

RESULTS AND DISCUSSION

Hydroponic plants are those cultivated using the hydroponic method, which is a cultivation technique that does not involve the use of soil as a growing medium. Instead, hydroponic plants thrive in a nutrient solution containing all essential elements required for optimal growth [5], [6].

The double rotary table hydroponic system is essentially similar to conventional hydroponic systems, with the main distinction lying in the utilization of a growing medium positioned on a rotating wheel. In this manner, the system illumination requires only one lamp placed at the center of the growing medium. Another uniqueness is that, with this method, plant roots are not continuously submerged in water.

The design of the double rotary table hydroponic system in this study can be observed in **Fig. 2** below, representing the 3D design of the hydroponic machine with a double rotary table system.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	rangka test	NONE	1
2	Roller	NONE	4
3	Rotary garden Plant	NONE	4
4	Water pipe	NONE	1
5	BRUSHLESS DC PUMP	NONE	1
6	Panel	NONE	1
7	Motor listrik	NONE	2
8	Dudukan Motor	NONE	2
9	Puli	NONE	6
10	V-Belt	NONE	2
11	Lampu tabung 50 Watt	NONE	4

Fig. 2. Design of the Double Rotary Table Hydroponic System

The design of this rotary hydroponic machine adopts the Drip System as the main flow system. Its principle involves the direct flow of water to the main module through capillary pipes. After reaching the main module, water drips back into the nutrient water container, forming a continuous cycle. The rotation cycle of the rotary hydroponic system is controlled through an integrated control panel with temperature, humidity, and pH sensors. Specifically, this control panel ensures optimal control over the plant growth environment. The lighting in this system is sourced from tube lamps with a power capacity of 40–50 watts, supporting efficient plant growth in indoor hydroponic environments. Thus, the integration of technology and careful control ensures the hydroponic machine's performance meets the needs of the cultivated plants.

In the analysis of the double rotary table hydroponic system, calculations of components and frame strength are performed based on the designed double rotary table hydroponic machine.

1. Component Calculation

Calculation of component revolutions

In this design, there are two electric motors utilized. Additionally, the system incorporates two pulleys with respective diameters of 75 mm (D1) and 75 mm (D2), along with a rotary table with a diameter of 700 mm (D3). The planned gearbox ratio is 1:20. The targeted rotational speed for the rotary table is 3 rpm, facilitating the calculation of component revolutions.

a) Rotation on pulley 2 (n3) [7],[8]

During the rotation on the rotary table, it can be determined using the following equation:

$$n3 = n4 \times \frac{D3}{D2} = 3\ rpm \times \frac{700\ mm}{75\ mm} = 28\ rpm \quad (1)$$

So, the rotation of pulley 2 was obtained at 28 rpm.

b) Rotation on pulley 1 (n2)

In the rotation on pulley 1, it can be determined using the following equation:

$$n2 = n3 \times \frac{D2}{D1} = 28\ rpm \times \frac{75\ mm}{75\ mm} = 28\ rpm \quad (2)$$

So, the rotation on pulley 1 is obtained at a rate of 28 rpm.

c) Rotation on gearbox [8]

The gearbox used in the design is known to have a ratio of 1:20, resulting in the shaft rotation magnitude after passing through the gearbox as follows:

$$putaran\ poros = \frac{1}{rasio} \times n2 = 20 \times 28\ rpm = 560\ rpm \quad (3)$$

So, the rotation on the axis is obtained at 560 rpm.

d) Electric motor rotation (n1)

The rotation of the direct electric motor can be determined due to the axis connected to the coupling shaft, which is linked to the gearbox shaft, resulting in a rotation speed of 560 rpm on the electric motor.

2. Motion force

Motion force is determined in the rotation that occurs in the simulation of the doble rotary table apparatus; subsequently, the occurring force can be calculated as follows.

Force on the rotary table:

Assuming the weight of the rotary table along with the hydroponic plants is 45 kg, the load or force that occurs can be calculated.

$$F = m \times g \quad (4)$$
$$F = 45\ kg \times 10\ m/s^2$$
$$F = 450\ N$$

Subsequently, the torque on the rotary table is calculated. It is known that the radius of the rotary table is 350 mm and the load or force on the cylinder is 450 N. Therefore, the occurring torque can be calculated using the following equation:

$$T = F \times r \quad (5)$$
$$T = 450\ N \times 0{,}35\ m$$
$$T = 157.5\ Nm$$

The power required to drive the rotary table:

$$P = \frac{T \times n}{63000} \quad (6)$$
$$P = \frac{157.5Nm \times 560\ rpm}{63000}$$
$$P = 1{,}402\ HP$$

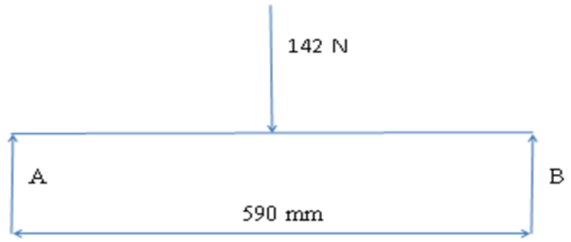
Based on the above calculations, the motive power required to drive the rotary table is determined to be 1,402 horsepower.

3. Shaft Calculation

The planned shaft diameter is known to be 25 mm with a length of 1620 mm. Subsequently, the assumed weight of the rotary table is 45 kg. Two shafts are employed to support the rotary table, thus each shaft bears half of the rotary table's weight, amounting to 22.5 kg. Following this, the material used is AISI 1045 Steel, which has a tensile strength of 580 N/mm² and a yield strength of 305 N/mm². The applied safety factor is 3, resulting in an allowable tensile strength of:

$$\sigma_{izin} = \frac{580\ N/mm^2}{3} = 193{,}33\ N/mm^2$$

Subsequently, the calculation of shaft strength can be determined by utilizing the torque moment equation as follows:



Torque Moments

$$M = F \times R \qquad (7)$$
$$M_A = F \times R/2$$
$$M_A = 225\ N \times \frac{1{,}62m}{2}$$
$$M_A = 182{,}25\ Nm$$
$$M_A = M_B = 182{,}25\ Nm$$

Stress

The planned shaft diameter is 25 mm or 0.025 m, then the stress equation can be determined as follows:

$$\tau = \frac{16 \times M}{\pi \times d^3} \qquad (8)$$
$$\tau = \frac{16 \times 182{,}25\ Nm}{3{,}14 \times (0{,}025\ m)^3}$$
$$\tau = 59.434.394{,}90\ N/m^2$$
$$\tau = 59{,}43\ N/mm^2$$

The shear stress is determined to be 59.43 N/mm².

Based on the calculations, the shear stress of the shaft is found to be 59.43 N/mm². The allowable shear stress for AISI 1045 steel is known to be 193.33 N/mm². Since the shear stress of the shaft is less than the allowable shear stress, AISI 1045 steel is deemed suitable for the design of the shaft in the hydroponic rotary table machine.

4. Calculation of V-belt length .

In the calculation of V-belt length, it can be determined by measuring the distance between the two pulleys from the center point. The distance between pulley 1 and pulley 2 is 245 mm, with respective diameters of pulley 1 (d1) at 75 mm and pulley 2 (d2) also at 75 mm. The length of the V-belt can be calculated using the following equation:

$$L = 2C + \left[\frac{(d_2+d_1)\pi}{2}\right] + \left[\frac{(d_2-d_1)^2}{4 \times C}\right] \qquad (9)$$

V-belt length

$$L = 2 \times 245\ mm + \left[\frac{(75+75)\,mm \times 3{,}14}{2}\right] + \left[\frac{(75-75)^2 mm^2}{4 \times 245\ mm}\right]$$
$$L = 490\ mm + 235{,}5 + 0$$
$$L = 725{,}5\ mm$$

The length of the V-belt obtained is 725.5 mm.

5. Framework Strength Simulation [9]**.**

In this analysis, a simulation of the strength of the hydroponic rotary table frame was conducted. It is assumed that the total load on the frame is 90 kg. The strength simulation was performed using SolidWorks 2023 software, and the parameters considered include Von Mises stress, displacement and safety factor [10]. The material used in the simulation is ASTM A36 Steel**. Fig. 3** below depicts the results of the simulation.

a) Results of Von Mises Stress Data Simulation

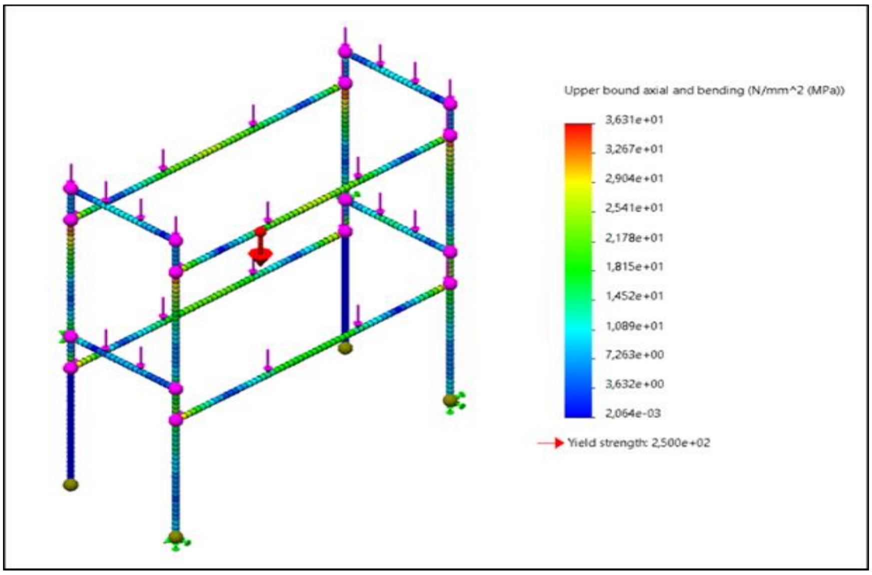


Fig. 3. Von Mises Stress Simulation Results.

The Von Mises stress is a method for measuring material failure by analyzing the resultant of the three principal stresses, commonly referred to as Principal Stress. Failure is estimated to occur when the Von Mises stress exceeds the material yield strength (σv > σy). In **Fig. 4** above, colors reflect the values of Von Mises stress, visible next to the frame model. Points with the highest Von Mises stress are located at the frame's corners, marked in red. The maximum Von Mises value is 3.631e+01 MPa, while points with the lowest values are indicated in dark blue, with a Von Mises value of 2.064e-03 MPa. The maximum stress does not exceed the yield strength of 2.5e+02 MPa, indicating that this bracket can be considered safe for use.

c) Simulation Data Results: Displacement

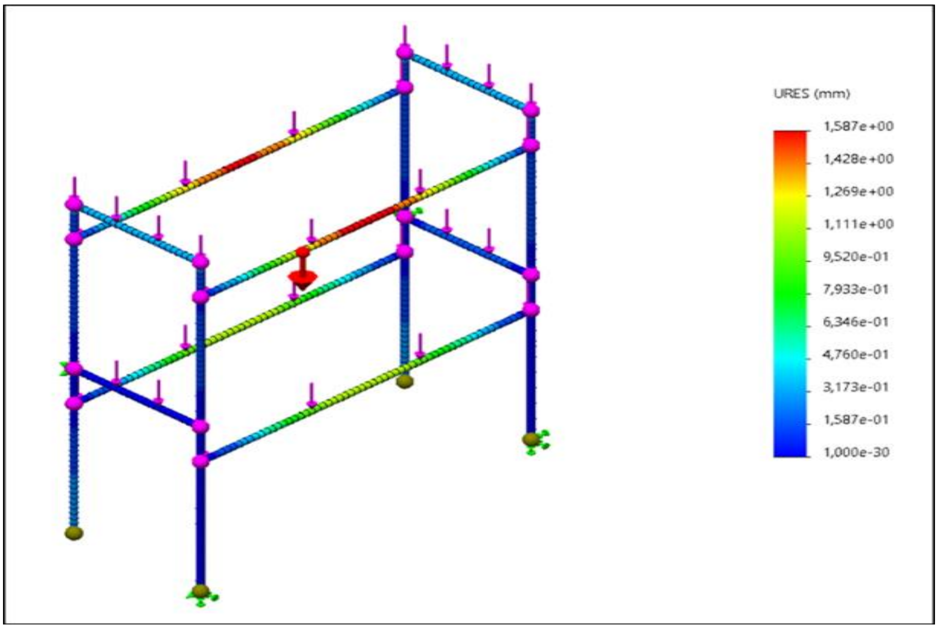


Fig. 4. Simulation results of displacement.

In the presented **Fig. 4,** the displacement due to the load on the loaded frame structure is evident. The maximum displacement is 1.587e+00 mm, while the minimum displacement is 1.000e-30 mm.

d) Results of Factor of Safety Simulation Data

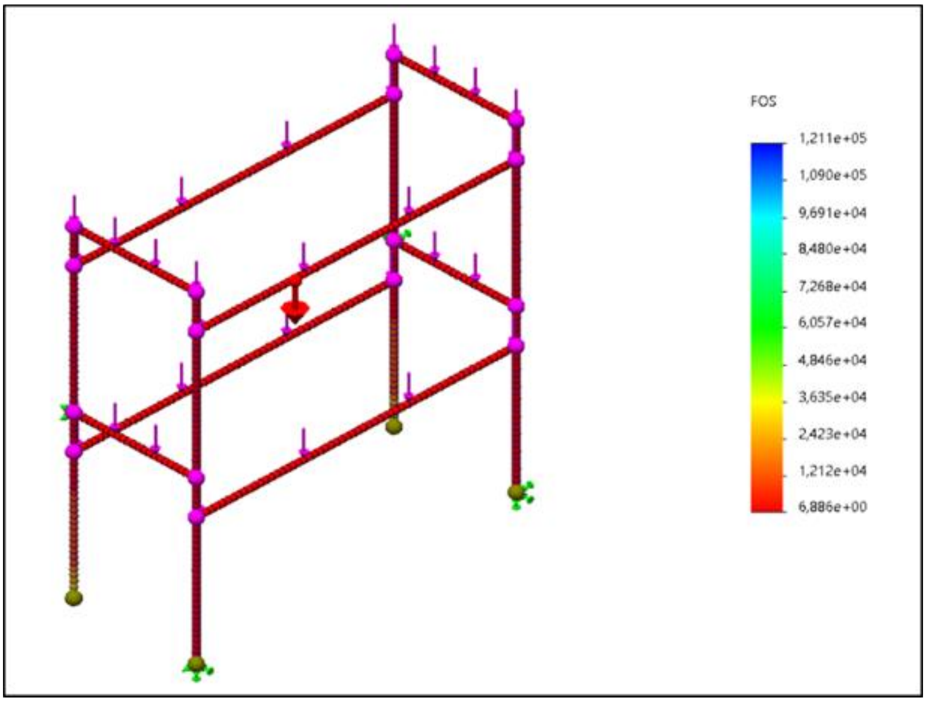


Fig. 5. Simulation results of the factor of safety.

In the **Fig. 5** above, the factor of safety on the frame loaded with loads 1 and 2 is known. The maximum value of the factor of safety is 1.211e+05, and the minimum is 6.886e+00.

Based on the calculations performed on the double rotary table hydroponic machine components, the following information can be provided:

1. The rotation of the component is known; the rotation on the electric motor shaft is 560 rpm, whereas the initially planned rotation on the rotary table is 3 rpm with a transmission of two pulleys, each 75 mm, and a gearbox ratio of 1:20.
2. The rotary table's driving power is determined to be 1.402 HP after obtaining the rotation speed in rpm on the motor shaft and the torque on the rotary table. According to these calculations, a 1.5 HP electric motor can be used in this design.
3. For the design of the rotary table shaft, the planned material is AISI 1045 steel with a yield strength of 193.33 N/mm², a diameter of 25 mm, and a length of 1620. The applied load is the rotary table weighing 45 kg. The calculated stress on the shaft is 59.43 N/mm². Considering the permissible stress value for AISI 1045 steel, which is 193.33 N/mm², and since the calculated stress is less than the permissible stress, AISI 1045 steel can be used for the design of the hydroponic rotary table shaft.
4. In the calculation of the V-belt length, the obtained value is 725.5 mm with a center point distance of 245 mm between pulley 1 (75 mm) and pulley 2 (75 mm). Based on the standard V-belt length, the approximate length for the hydroponic rotary table V-belt design is 29 inches or 737 mm.

The discussion of the structural strength that has been conducted through static simulation of the frame's strength using SolidWorks 2023 can be seen in **Table 1.**

Tabel 1. Simulation Results of Static Strength for the Rotary Table Hydroponic System Frame Using Solidworks 2023.

Simulation	Max	Min	Yield of strength
Stress Von misses	3,631e+01 Mpa	2,064e-03 Mpa	2,500e+02 Mpa
Displacement	1,587e+00 mm	1,00e-30 mm	-
Factor of safety	1,211e+05	6,886e+00	-

Based on the data in Table 1 above, it is known that the maximum and minimum stresses in the frame with a total load of 90 kg are 3.631e+01 MPa and 2.064e-03 MPa, respectively. These values do not exceed the yield strength of the ASTM A36 steel material used in the frame, which is 2.500e+02 MPa, indicating that the frame is safely usable. Furthermore, the maximum and minimum displacements are determined to be 1.587e+00 mm and 1.00e-30 mm, respectively. The maximum and minimum values of the factor of safety are 1.211e+05 and 6.886e+00, respectively. These values exceed the factor of safety range recommended by Dobrovolsky in his book "Machine Element," where the safety factor for static loads is suggested to be in the range of 2.0 - 3.0. Therefore, the frame can be used in the design process.

CONCLUSIONS

Based on the results of the design of this double rotary table hydroponic system, the following conclusions can be drawn:

1. The dimensions of the rotary table hydroponic machine in this design are 1570 x 600 x 2360 mm, with a frame made of 30 x 30 mm and 2 mm thick galvanized hollow steel profiles.
2. From the planned rotation of the rotary table at 3 rpm, the required power for the machine is determined to be 1.402 HP. Therefore, an electric motor with a power rating of 1.5 HP can be used in the design.
3. The planned material for the rotary table shaft in this design is AISI 1045 steel, with a strength of 193.33 N/mm2, a diameter of 25 mm, and a length of 1620 mm.
4. Based on the standard v-belt length, the v-belt length suitable for the design of the rotary table hydroponic machine is found to be 29 inches or 737 mm.
5. The maximum and minimum stresses on the frame with a total load of 90 kg are 3.631e+01 MPa and 2.064e-03 MPa, respectively. These values do not exceed the yield strength of the ASTM A36 steel used in the frame, which is 2.500e+02 MPa, ensuring the safety of the frame. Additionally, the maximum and minimum displacement values are 1.587e+00 mm and 1.00e-30 mm.
6. The maximum and minimum safety factors obtained are 1.211e+05 and 6.886e+00, respectively. These values exceed the range of safety factors for static loads, which is 2.0 - 3.0. Therefore, the frame can be safely used in the design.

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