Original Research Article

Development and Evaluation of a Helical Ribbon-type Mixer for Mushroom Substrate

ABSTRACT

Manual substrate mixing for mushroom production such as rice straws, sawdust, and banana leaves is laborious and time-consuming. Substrates need to be thoroughly mixed to produce mushrooms of good quality. This study was done to design, fabricate, and evaluate the performance of a helical ribbon-type mixer. The performance of the ribbon-type mixer was evaluated in terms of the mixing capacity and mixing efficiency. Loading weight (5kg, 10kg, and 15kg) and operating speed (11-15rpm, 16-20rpm, and 21-25rpm) of the machine were used as the performance parameters. Analysis of Variance (ANOVA) for Factorial Experiment in Completely Randomized Design (CRD) was used to analyze the results while comparison among treatment means was tested at 5% level of significance using Duncan's Multiple Range Test (DMRT). Results revealed that the highest machine capacity of 226.67 kg/hr was attained at a loading weight of 15kg and an operating speed of 21-25rpm. Maximum mixing efficiency (95.27%) was achieved with the combination of 15 kg loading weight and an operating speed of 11-15 rpm. The initial investment in fabricating the substrate mixer for mushroom production was Php 21, 713. Operating the substrate mixer for mushroom production had a projected annual cost of Php 3,655.475. Break – even weight was 91,795.24 kg of substrates per year at a custom rate of Php 0.35 per kilogram.

Keywords: machinery design, mushroom mixer, ribbon-type, substrate, mixing

1. INTRODUCTION

According to the Food and Agriculture Organization (2022), global mushroom production skyrocketed from 13.8 to 42.8 million tons over the 30 years from 1990 to 2020. Mushrooms were one of man's earliest foods and often considered exotic. In the West, mushrooms are regarded as a luxury food. But in many developing countries like the Philippines, mushrooms can mean cash for the poor and a new source of nutrition. Mushrooms are even more suited throughout areas rich in plant wastes such as sawdust, sugarcane bagasse, and others (Quimio, 2004).

Since 1995, the mushroom industry in the Philippines has become severe. In 2009, the minimum production volume that had been produced was 355 metric tons (MT). Because of the low production cost and ample cheap substrates from agricultural waste products, mushroom farming in the Philippines has become practicable providing extra income to the mushroom growers, especially in the rural or remote areas.

Moreover, mushroom cultivation is a useful method of environmental waste management and waste disposal. Agricultural wastes such as rice straw, sawdust, and dried banana leaves will be used as substrates for mushroom production. Mixing plays a vital role in the success of mushroom production because it is the only way to be certain that all substrate has the required water and has been heated to the required temperature. Mixing may be required to bring in cool air, to bring the temperature down to approximately 25°C. The cooled substrate is then spawned (inoculated) and packed into polyethylene bags for growing (Kurtzman, 2010).

In addition, mixing equipment must be designed for mechanical and process operation composed of a mixing tank or chamber, mixing device, discharge chute, and a prime mover. Although mixer design begins with a focus on process requirements, the mechanical design is essential for successful operation (Dickey et al, 2004). A mixer is a machine that mixes two or more substances to mingle uniformly with substances of different sizes, moisture content, and bulk density. The material for fabricating the mixer should not be corrosive and can resist stress (PAES 258:2011).

Unfortunately, little available information and literature on locally available designs of mushroom substrate mixers in the Philippines. The importance of mixing the substrate is an important process before the pasteurization process as it provides a balanced nutritional composition that directly enhances the yield of *Pleurotus ostreatus* because of the carbon-nitrogen optimization (Philippoussis et al., 2009) caused by consistent texture and porosity which can be achieved by mechanical mixing. It also increases water retention and moisture as related by Yang et al. (2013) that uniform mixing of substrates is essential as it ensures that mycelium has constant access to nutrients and moisture thereby increasing yield and productivity (Shah et al, 2004).

Interestingly, according to mushroom growers in the locality, uniformity of substrate can reduce contamination rates, making healthier and more productive mushroom crops due to consistent mixing. Surveys and informal interviews with mushroom growers in the Province of Nueva Vizcaya (Philippines) showed that mixing was done manually. This technique is labor-intensive and time-consuming. Hence, this study was conducted to develop a mechanical mixer that would contribute to increasing mushroom production.

This study was then conducted to develop and evaluate a substrate mixer for mushroom production to improve the production capacity of mushroom producers.

2. MATERIALS AND METHODS

2.1 Design Considerations

The device was designed with consideration to the following criteria:

1. The internal stresses caused by the external loads;
2. The motion of the moving parts or the kinematics of the machine;
3. The materials that will be used are materials available in the local market;
4. The safety of operation (provide a safety device for the safety of the operator); and,
5. Cost of Construction.

2.2 Design of the Machine Components

2.2.1 Loading Hopper

It is an inverted frustum pyramid shape that serves as the entrance or passage of the substrates. The dimensions of the hopper is 310mm x 310mm and made from gage 16 (0.6mm thick) stainless steel sheet. The inclination of the hopper was 60° to cause materials with high moisture content to fall easily.

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2.2.2 Mixing cylinder/chamber

Locally available materials were used to fabricate the U-shaped mixing cylinder or chamber. The mixing process was caused by the rotating shaft inside the cylinder. It was made up of stainless-steel metal sheets 0.6mm thick and 1 meter in length.

2.2.3 Ribbon screw conveyor

It served as the agitator to mix the substrates. It was made up of 10mm thick and 20mm wide steel flatbar with a mass per unit length of 1.57kg/m (PAES 316:2002). It was designed with helices having a uniform diameter of 600mm and a pitch of 150mm. The ribbon was supported by a smooth round steel bar as a rasp bar with a diameter of 10mm. The peg tooth was also made up of a smooth round steel bar with a diameter of 10mm. The mass per unit length of the round steel bar is 0.617 kg/m (PAES316:2002).

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2.2.4 Mixer shaft

It is the rotating part in the center of the mixing chamber that transfers power. The shaft was made up of stainless steel with a designation of 304. The total force that the shaft can carry was 384.06 N and the maximum allowable shear stress for stainless steel shaft was 41.369 MPa with a safe shear stress factor of 1.0. Using equation 1, the diameter of the shaft was 36mm which was supported by a bearing.

$$d = \sqrt[3]{\frac{16T}{\pi\tau}} \quad (1)$$

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where:
T = Torque acting upon the shaft, N-m
τ = maximum allowable shear stress, Pa
d = diameter of mixer shaft, m

2.2.5 Power required

The maximum load that the mixing chamber can carry was 49.15 kg. The equations 2 and 3 were used in determining the required torque and power.

$$P = 2\pi TN/60 \quad (2)$$

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$$T = F \times r \quad (3)$$

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where:
P = power requirements, watts
T = torque developed on the mixing chamber, N-m
F = force acting on the mixing chamber, N
r = radius of the helices of the ribbon screw conveyor, m
N = speed of the mixing chamber, rpm

Based on the maximum loading weight, the computed torque was 145 Nm. The highest speed was 21-25 rpm, while the substrate mixer's power requirement was 380 watts.

2.2.6 Diameter of the pulley

Power transmission was performed through the pulley and belt assembly. A 1.5hp single phase, 1100 rpm speed was used as prime mover.

$$D_2 = \frac{N_1 D_1}{N_2} \quad (4)$$

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where:
N1, N2 = speeds of motor mixing auger respectively, rpm
D1, D2 = diameters of the motor pulley and mixing auger pulley respectively

Using equation 4, the three (3) sizes of pulley, i.e., 76.2mm, 101.6mm and 152.4mm were used to obtain the
three levels of operating speed.

Using the equation 5, the belt length for an open drive was calculated.

$$L = 2C + 1.57\,(d_1 + d_2) + \left(\frac{d_1 - d_2}{4C}\right)^2 \quad (5)$$

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where:
L = belt length, m
C = center distance between pulleys, 16m
d_1 = pitch diameter of driver pulley, m
d_2 = pitch diameter of driven pulley, m

2.2.7 Discharge outlet

It serves as the collecting area for the substrate after the mixing operation. It was made up of gage 16 (0.6mm) galvanized steel sheet with a dimension of 210mm x 390mm.

2.2.8 Supporting frame

It is a structure that supports the machine without collapsing. It was primarily made up of mild steel angle bars.

2.3 Principle of Operation of the Machine

The principle of operation of the mushroom substrate mixer is very simple. The mushroom substrate mixer was designed to mix thoroughly the ingredients of the substrates. In this study, the substrates used were rice straw, dried banana leaves, and sawdust. The electric motor was first started and allowed to operate at no load for a few seconds before loading the substrate in the loading hopper. The rotating action of the ribbon screw conveyor caused the mixing operation of the chopped substrates with different sizes, shapes, and bulk density. The substrates moved towards the discharge outlet which allowed the substrates out of the mixing chamber for collection. Figure 1 shows the flow of the mixing operation from loading the substrates to the collection of mixed substrates.

Figure 1. Flow of Mixing Operation

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2.4 Preparation of Sample Materials

Substrates materials, i.e., rice straw, banana leaves, and sawdust with a total weight of 270 kg with different initial moisture content (162kg rice straw, 27 kg dried banana leaves, and 81 kg sawdust). These agricultural wastes were chopped for about one inch in length. After chopping, water was then added to the materials to reach a moisture content of 50% - 60%. The substrates were checked and inspected to make sure it was free from foreign materials or insects that could contaminate the substrates before subjecting them to mixing operation.

2.5 Final Testing and Evaluation

The mushroom substrate mixer was tested at three different speeds (11-15 rpm, 16-20 rpm, and 21-25 rpm) and three different loading weights of mixing (5kg, 10kg, and 15kg) with three replications. The performance of the mushroom substrate mixer was evaluated in terms of the machine capacity and mixing efficiency.

2.6 Evaluation of Performance Parameters

The mushroom substrate mixer was evaluated based on its machine capacity and mixing efficiency. Data gathered during the performance testing was recorded on a data sheet.

2.6.1 Machine Capacity

The machine capacity of the device is the amount of total input weight of the substrate per unit time during the actual mixing operation time, expressed in kilogram per hour. A known weight of the substrate was put into the machine. The capacity of the machine was computed using the equation:

$$M_c = \frac{W_T}{T_o} \quad (6)$$

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where:
M_c= machine capacity, kg/h
W_T= total weight of substrate input, kg
To = total operating time, h

2.6.2 Mixing Efficiency

The performance of the substrate mixer for mushroom production was evaluated based on the mixture ratio (60:30:10 by weight) of the substrate. Five hundred grams (500g) of sample materials were taken after the mixing operation. The following equations were used:

$$\%RC = \frac{weight\ of\ rice\ straw}{total\ weight\ of\ sample\ substrate} \times 100 \quad (7)$$

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$$\%SD = \frac{weight\ of\ saw\ dust}{total\ weight\ of\ sample\ substrate} \times 100 \quad (8)$$

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$$\%BL = \frac{weight\ of\ banana\ leaves}{total\ weight\ of\ sample\ subtrate} \times 100 \quad (9)$$

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$$ME = \%RC + \%SD + \%\ BL \quad (10)$$

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where:

ME = Mixing Efficiency, %
%RC = percentage of rice straw
%SD = percentage of sawdust
%BL = percentage of banana leaves

2.7 *Statistical Analysis*

Three levels of speed (rpm) of the mixing chamber were used to determine the optimum operating speed. Three levels of loading weight of mixing were also considered in conducting the test. The experimental units were tested following the Completely Randomized Design (CRD) experiment.

The test Factors and their level of combination are the following:

Factor A – Loading Weight
A1: 5kg
A2: 15kg
A3: 20kg

Factor B – speed of the mixing chamber
B1: 11-15 rpm
B2: 16-20 rpm
B3: 21-25 rpm

The results obtained were analyzed using Factorial Analysis (3 x 3 x 3) in ANOVA for Completely Randomized Design (CRD) experiment. The sources of variations were presented in ANOVA table at 5% level of significance. Duncan's Multiple Range Test (DMRT) was used in the comparison between treatment means.

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2.8 Cost Analysis

Cost analysis was performed to determine the cost of mixing using the device and the cost of mixing without using the device. The following equations were used in computing the parameters such as fixed cost, variable cost, and cost of mixing (Sta. Maria, 2000).

2.8.1 Depreciation

$$d = (IC-SV)/L \quad (11)$$

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Where:

d = depreciation, Php/yr
IC = initial cost, Php
SV = salvage value, 10% of IC
L = life span of the machine, yrs

2.8.2 Average investment

$$AI=(IC+SV)/2 \quad (12)$$

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Where:

AI = average on investment, Php
IC = initial cost
SV = salvage value

2.8.3 Fixed Cost

$$FC= d+AI+I \quad (13)$$

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Where:

FC = fixed costs, Php/yr
d = depreciation, Php/yr
I = Insurance and license, 2% of average investment/yr
AI = average on Investment, Php

2.8.4 Labor Cost

The machine was operated by two people at a rate of Php 350/day.

2.8.5 Electricity

A 1.1 kW electric motor was used to power the machine at Php 11/kW-hr as the current prevailing rate.

2.8.6 Repair and Maintenance

These costs can vary greatly depending on operating conditions, management, maintenance programs, and local costs which was expressed in equation 14.

$$RM = (12\%\ IC)/L \quad (14)$$

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Where:
RM = repair and maintenance, Php/yr
IC = initial cost, Php
L = lifespan of the machine, yrs

2.8.7 Variable cost

$$VC = Lc + E + RM \quad (15)$$

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Where:
VC = variable cost, Php,yr
Lc = labor cost, Php/yr
E = electricity, Php/yr
RM = repair and maintenance, Php/yr

2.8.8 Custom rate

$$CR = (Lc/OT)/AMC \quad (16)$$

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Where:
CR = custom Rate, Php/kg
Lc = labor cost, Php/day/laborer
OT = operating time, hr
AMC = actual mixing capacity, kg/hr/laborer

2.8.9 Cost of Mixing per kg of substrate

The cost of mixing per kilogram of mixed substrates using the machine was determined by the equation:

$$Mc = AFC/W + VC/C \quad (17)$$

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Where:
Mc = cost of mixing, Php/kg
AFC = annual fixed cost, Php/yr
W = total weight to be mixed, kg/yr
VC = variable cost, Php/hr
C = machine capacity, Kg/hr

2.9.0 Break – even Point

The Break-even Point is the point in the break-even graph where the custom rate and the weight of mixed substrates meet. At this point, the determined weight of substrates is the minimum weight at which the annual cost will be even with the profit.

$$BEP= AFC/((CR-VC/C)) \quad (18)$$

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Where:

BEP = break– even point, kg
AFC = annual fixed cost, Php/yr
CR = cost of mixing per kilogram, Php
VC = variable cost, Php/yr
C = mixing capacity of the machine, kg/hr

3. RESULTS AND DISCUSSION

The Developed Substrate Mixer

Figure 2. Pictorial view of Fabricated Substrate Mixer

3.1 Performance Evaluation of the Device

3.1.1 Machine Capacity

The capacity of the machine using different speeds of operation and loading weight is presented in Table 1.

Table 1. Mean Machine Capacity as affected by loading weight and operating speed

LOADING WEIGHT	OPERATING SPEED	REPLICATIONS 1	2	3	MEAN
5	11-15	108.7	147.06	135.14	130.3[b]
	16-20	131.58	138.89	125	131.82[b]
	21-25	131.58	128.21	138.89	132.89[b]
10	11-15	256.41	151.52	188.68	198.87[a]
	16-20	200	227.27	204.08	210.45[a]
	21-25	200	212.77	227.27	213.35[a]
15	11-15	230.77	150	220.59	200.45[a]
	16-20	217.39	197.37	220.59	211.78[a]
	21-25	234.38	245.9	200	226.76[a]

Means not sharing letters in common within columns differs significantly by DMRT at 5 % significance level.

The result showed that the highest machine capacity was attained with the combination of 15 kg loading weight and 21-25 rpm operating speed with a mean of 226.76kg/hr while the lowest mixing capacity was attained at the combination of 5kg loading weight and 11-15 rpm operating speed of the mixing assembly with a mean of 130.30 kg/hr. This was because as the operating speed increases as the loading weight increases.

Based on the results, it was observed that the machine capacity was dependent on the operating speed. The machine capacity of the device increases as the operating speed and loading weight increases. Results showed that the machine capacity increased from 11-15 rpm to 21-25 rpm for the different loading weights of the substrate. The capacity of the machine was greater when operating at a high speed because the mixing assembly had the ability to rotate faster, and the substrate will easily reach the discharge outlet.

3.Mixing Efficiency

The highest mixing efficiency obtained during the testing was 95.27 %, which was the result of a loading weight of 15 kg at an operating speed of 11-15 rpm. This obtained efficiency is almost the same with the results (95.96%) of Adenigba and Patrick (2018) but higher than the mixing performance (86.91 %) of a paddle shaft mixer developed by Bekele (2020). While the lowest mixing efficiency obtained was 92.07 % which was the result of the combination of loading weight and operating speed of 15 kg and 21-25 rpm. These results showed no significant differences among the different treatments which means that at any given combination of the loading weight and operating speed, the machine's performance was efficient in terms of mixing operation. Any of the combinations can achieve good enough mixing efficiency.

The mixing efficiency of the machine was high when operating at low speed because as the substrate rotates within the mixing assembly inside the mixing cylinder the more it was mixed. The moisture content of the substrate was one factor that can affect the mixing efficiency of the machine. This was because when moisture content is high the substrates were compacted with each other making it hard to mix thoroughly.

Cost Analysis

Cost analysis was performed to determine the annual cost of operation and return on investment using the substrate mixer for mushroom production. From the basic assumptions considered, the substrate mixer had a break – even weight, as presented in Figure 3, of 91,795.24 kg of substrates, enough to return in one year.

From the relationship (cost of mixing per kilogram and quantity of substrates), the machine could earn a profit when the quantity of substrates to be mixed will be greater than the break - even weight at a custom rate of Php 0.35 per kilogram, otherwise the machine is expensive to use.

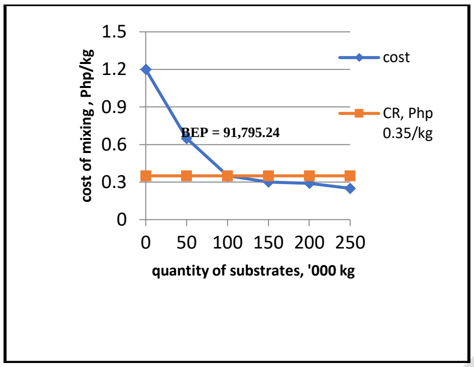

Figure 3. The break-even point of the mixing operation using the developed mixer

4.CONCLUSIONS

The developed substrate mixer demonstrated high efficiency which could significantly reduce labor and time required for substrate preparation in mushroom production. The adoption of this mixer machine enhances mixing uniformity, translating to improved yield and productivity in mushroom cultivation.

5.RECOMMENDATIONS

From the findings and conclusions, the following were recommended to further improve and explore the machine: 1) the clearance between the mixing cylinder and the mixing device at both ends especially at the discharge outlet should be greater than the designed clearance; 2) all the spiral assembly of the screw conveyor should have peg tooth to lessen the amount of substrate that was left in the cylinder after the operation; 3) the diameter of the screw conveyor must be less than 0.6m to mix thoroughly the substrate and reduce the time of mixing; 4) for ease of operation especially turning ON and OFF, a switch button must be installed.

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