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Energetic Assessment of Different Paddy Straw Densification Processes

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Densification and handling of crop residue, especially paddy straw is a critical issue due to very high moisture content as well as relative humidity and abundant amount. In the present study, different densification processes using field balers and stationary balers were evaluated in chopped and full-length paddy straw. In the study, it was found that minimum energy was required for T_1 (50.16 MJ·t^{-1}) followed by T_2 (102.65 MJ·t^{-1}), T_3 (117.57 MJ·t^{-1}), T_4 (144.53 MJ·t^{-1}) and T_5 (152.53 MJ·t^{-1}). There was a significant ($p < 0.0001$) variation in energy consumption between the different techniques used in the research. The scented variety of rice is mostly harvested manually. The densification of full-length paddy straw by a hydraulic press type fixed baler was found appropriate with baling capacity (1.13 t·h^{-1}), lowest energy requirement (50.16 MJ·t^{-1}), and volume compaction ratio (6.87). In the case of combine harvested paddy, treatment T_2 was found most appropriate with maximum field capacity (0.54 ha·h^{-1}), bailing capacity (4.43 t·h^{-1}), and volume compaction ratio (5.26). Treatment T_2 also has a minimum man-hourtime requirement for straw handling and bailing (3.57 man-h·t^{-1}) out of which bailing of straw takes 0.44 h·t^{-1} and consumes 102.65 MJ·t^{-1} energy. Based on the present study the farmer can decide the best densifying method for paddy straw among the selected treatments. Thus, the outcomes of the research will be helpful for the aligned industry as well for the farmer.

Keywords: Baler, Energy, Hey rake, Residue, Straw management, Stubble

Introduction

The world is facing many problems concerning air pollution and change in the environment due to human activities such as paddy residue burning, fossil fuel usage, chemical usage, nuclear waste, etc. Biomass is the world's third-largest energy resource, after coal and oil.[1] In the agriculture sector, the burning of crop residue is a major problem for the environment and living beings. Gaseous emissions from crop residue burning can result in serious health risks, chronic bronchitis, aggravating asthma, and decreased lung function.[2] Burning causes almost complete nitrogen loss, phosphorus loss of about 25 percent, potassium loss of 20 percent, and sulphur loss of 5 to 60% from the soil.[3] In India, a large portion of the residue is burnt on-farm primarily to clear the field for sowing of the succeeding crop. Government of India has estimated that about 500–550 million tonnes of crop residue are generated every year.[4] From the total crop residue, cereal crops (rice, wheat, maize, and millet) contribute 70% while rice crops alone contribute 34%.[5] The agricultural residue has tremendous use viz., animal feed, soil mulch, bio manure, covering for rural homes, and as fuel for domestic and industrial use.

The farmers can adopt mechanized methods of straw removal or in-situ management of crop residue.[6] The straw removal method includes the use of stubble shaver, hay rake, and baler where in-situ management of paddy straw can be done by two methods i.e., residue incorporation and residue retention.[6] In the residue incorporation method, the residue is chopped and mixed into the soil and in the residue retention method, the residue is left uniformly over the field.[7] Baling or densification is the process of increasing the density of straw by applying force. It is also known as compaction. The baling or densification of paddy straw can be done by using a field straw baler which is also known as a hay baler. It is a farm machine utilized to compress a cut and raked crop (such as straw, hay, salt marsh hay, or silage) into compact bales that are easy to handle, store, and transport. The straw bale formed has wide usages in industry for making cardboard, papers, and insulation material, in thermal power plants for power generation, for packing the materials, and for mushroom cultivation, it can be processed as enriched feed by mixing molasses and oil cakes which can be fed to camels, goats, cattle, for ethanol and biogas generation and as fuel in brick kilns.

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Several studies on these strategies have been published in recent years. *Sharma & Chandel*[8] *examined t*he straw removal technology by baling and concluded bailing may provide an economical, attractive, and environmentally safe option. Mangaraj & Kulkarni[9] also worked on the removal of technique and found the collection, gathering, and baling of straw was considered to be a more appropriate approach to straw management to make the field free of loose straw without straw burning in the field. Straw bale construction can be one of the most excellent choices for all kinds of individuals for developing an economic building with sustainable materials.[10] Around 120,000 tonnes of rice straw is gathered each year in India to add 12 megawatts of electricity to the local power grid. The growing demand for rice straw needs the use of larger balers, such as the commercial CLAAS Markant 55.[(11)]

The baling operation can be performed manually and mechanically. Manual densification (bulging) of loose straw or hay material is done by pressing it by feet and putting whole body weight on it. Bulging gives about 20% of compaction to the loose material.[12] Manual baling is not much effective, its efficiency is very low as compared to mechanical baling, there is more fatigue and it is a very slow process. Loose rice straw has a low density compared to rice husks, which have a density of between 86 and 114 kg m^3 untreated.[13] This means a larger volume per kilogram, which entails higher shipping and handling costs as well as more processing, transportation, storage, and burning issues.[14,15] Processing rice straw can reduce its volume, but it will take more energy.[16] Low bulk density promotes poor mixing and nonuniform temperature distribution (unfavourable operating conditions), which reduces energy efficiency.[17,18] Densification machines available in the country include, viz., field balers, moveable balers, and stationary balers. Mechanical densification of hay material is done by compacting it in a confined volume and this compaction is achieved using a pressure plate or arm operated by a crank using electrical or mechanical power. Furthermore, the volumetric weight of mechanically compacted straw bales is 50–100% higher than that of loose straw, resulting in significant savings in handling and transport expenses. High-density compaction (e.g., stationary compaction, briquetting, and pelletizing) can further increase the volumetric weight of baled straw from 400% to 700%, reducing transportation costs by more than 60%.[11]

Each type of baler generates a different shape of bale (cuboid or cylindrical) with a variety of sizes. Rice straw managed by mechanized collection and densification processes will improve the supply chain. Rice straw densification enhances by-product handling and storage, lowering transportation costs and making better use of storage facilities. As the government prohibits field burning of rice straw due to this mechanical bailing is becoming popular in India. Thus, the current study gives an in-depth knowledge of densification methods, transportation, and handling of paddy straw at the farmer and industrial utilization levels. However, the cost of straw densification machinery, as well as transportation and handling, may limit its acceptance. Sale of high-quality densified straw products during off seasons, the initial investment may pay off the expenses in a short period. It is difficult for a farmer to choose a suitable type of paddy densification machine as per field conditions. Thus, considering the above facts, research was conducted to measure energy requirements in the densification processes that will help farmers in choosing better methods for proper management of paddy straw as per their suitability.

Materials and Methods

Experimental Field Climate Characteristics

The experiments were conducted at village Ramba of District Karnal (Haryana), situated at an altitude of 253 m above sea level, and at village Pai of District Kaithal (Haryana), situated at an altitude of 224 m above sea level. Karnal and Kaithal have a semi-arid and sub-tropical climate with hot summers and cool winters. The soil of the experimental farm is classified as an alluvial soil group having a sandy loam texture.

Materials

Field baler, Stationary baler (*hydraulic press type*), Stubble shaver, Hay rake, Chaff cutter, tape, weighing machine, a metal box of 1 × 1 × 1 m^3 dimension, and oven.

Plan of Study

The harvesting of paddy in the selected field was done with a combine harvester and the study was planned with 5 different densification processes which are described below in Table 1, where different type of treatments is shown. For treatments, T_4 and T_5, the paddy straw used was of full length and chopped correspondingly. The harvesting of this paddy straw was done manually and dumped outside the field by the farmer. Hence, the man and energy involved in the collection of straw from the field are not taken into account for these treatments. The description of various machines used in the experiment is given below.

Field Baler: The field baler uses a tractor as a power source. It is movable and can also be installed at a particular place if required. The area of its compression chamber is 460 × 360. In this baler, the cross-section area of the bale made can be changed. Changes can be brought in the bale length of this baler by varying the running length of the tying mechanism. An automatic knotting mechanism is provided which ties the twine around the bale. Two knotters are operated by a twin-arm lever arrangement which engages or disengages the revolution of the knotter shaft. Picker fingers and reels are used as straw feeding systems. In the field baler, a hand lever is provided to increase or decrease the spring pressure which intends to control bale density through controlled convergence of the bale chamber at the rear side

Stationary Baler: Stationary Baler uses an electric motor as a power source. This electric motor supplies power to the hydraulic pump which operates the plunger. It is grouted and installed in one place. The cross-section area of the bale made in this baler can be changed. In a stationary baler, the bale density can be varied by varying the force acting on the hydraulic press. In stationary baler (hydraulic press type), the bales were tied manually by placing round twine around the bale through channels provided in the base plate and top plate of the compression chamber. In this Twine/GI wire is used as tying material. In stationary baler (hydraulic press type), bale length cannot be varied but, height can be varied.

Chaff Cutter: It is operated by an electric motor or PTO shaft of a tractor. The feeding of full-length straw is done through a trough. The trough has a conveyer belt at the bottom which conveys the feed to the cutting chamber. The cutting blades chop the full-length straw into small pieces.

Hay Rake: A hay rake is an agricultural implement that windrows the straw for further collection by a baler, loader wagon, etc. It is also designed to fluff up the hay and turn it over so that it may dry. It has four raking wheels has a total working width of 1.5 meters.

Stubble Shaver: A stubble shaver is a tractor-operated implement. Two rotating blades underneath a rectangular metal frame slash the standing stubbles in the field. Power to the two rotating blades is provided by the PTO of the tractor. The heavy-duty gearbox and rugged frame provided is capable of withstanding high load conditions like rough & tough wild grass, anchored straw, and bushes. It has a Vertical axis blade which generally operates at 789 RPM.

Energy

Man-hour Required

The number of man-hours required to perform a task was recorded and expressed as man-h·t^{-1}. Man-hours depended on the amount of work, type of work, type of baler used, etc. The specific work performed manually in different treatments was presented in Table 2

Fuel and Electricity Consumption

For measuring the fuel consumption of the tractor, the fuel tank was filled up to the neck before and after

Table 1 — Treatment details of the planned study

T_1	Bailing of straw by tractor-operated field baler after single operation of stubble shaver.
T_2	Bailing of straw by tractor-operated field baler after a single pass of stubble shaver and single operation hay rake.
T_3	Manual collection of full-length straw and fed into the field baler at a stationary position.
T_4	Densification of full-length straw in the stationary baler.
T_5	Chopping of full-length straw with chaff cutter and densification in the stationary baler.

Table 2 — Work performed manually in different treatments

Treatment	Baling	Collection & loading of bale
T_1& T_2	The man-h were recorded for tractor operator for operation of stubble shaver (T_1& T_2), hay rake (T_2), and baler (T_1& T_2)	The man-h were recorded for collection of bales produced by the baler and left at a different location in the field and then loading the same in the truck
T_3	The man-h were recorded for collection of loose straw left by the straw walker of the combine harvester and feeding of collected straw into the field baler	The man-h were recorded for loading bales from a single location into the truck
T_4	The man-h were recorded for feeding full-length straw into the stationary baler and tying the bale	The man-h were recorded for loading bales from a single location into the truck
T_5	The man-h were recorded for chopping the full-length straw and then feeding the straw into a stationary baler.	The man-h were recorded for loading bales from a single location into the truck

the operation at the same place. The amount of refilling fuel was measured, and that was the fuel consumption for operation. It was expressed in liters per hour by dividing the number of liters of fuel refilled by the time taken to operate the tractor. Power consumption was measured using a three-phase digital energy meter. The energy meter was connected between the input supply and the electric motor. As long as the electric motor was run, the electricity consumed of that motor was recorded in the energy meter.

Total Energy Required

The energy required was calculated by including the direct energy sources viz. human, fuel, electricity, and indirect energy sources viz. tractor and machinery.

Energy Input Equivalent

Total energy was calculated by multiplying the quantified man-h, diesel, electricity, tractor, and machinery with their energy equivalents.[7] Values of energy equivalents of the different source is given in Table 3.

Statistical Analysis

The treatments were replicated 4 times and a single-factor Randomised Block Design in the experiment was used for statistical analysis of the data at a 5% level of significance with the help of OPSTAT software (CCSHAU, HISAR).

Results and Discussion

Soil and straw samples were collected from the experimental field after 15 days of crop harvest and the moisture content of the soil ranged from 16.67% to 17.95% with an average of 17.23% (wb). The moisture content of straw varied from 19.11% to 22.93%. The average value of moisture content of straw collected from the field was 21.03% (wb). Due to the technique and duration of the straw's storage, the moisture content can vary substantially.[16,19]

The field capacity of balers under different treatments ranged from 0.05 $ha \cdot h^{-1}$ to 0.54 $ha \cdot h^{-1}$ as shown in Fig. 1. The field capacity of the field baler was also found similar by other researchers Sandhya *et al.*[20], Singh *et al.*[21] and Sharma & Chandel[8] to the above-depicted range. Variation was due to the different types of baler used in different conditions in the study. For the stationary balers under treatment T_4 and T_5, time was recorded and capacity was computed in terms of $ha \cdot h^{-1}$ for comparison with other treatments. The baling capacity of the baler ranged from 4.43 $t \cdot h^{-1}$ to 0.58 $t \cdot h^{-1}$. The maximum baling capacity was obtained for T_2 (4.43 $t \cdot h^{-1}$) followed by T_3 (2.32 $t \cdot h^{-1}$), T_1 (1.69 $t \cdot h^{-1}$), T_4 (1.13 $t \cdot h^{-1}$), and T_5 (0.58 $t \cdot h^{-1}$). The field baler under T_2 has the highest baling capacity whereas stationary baler under T_5 has the lowest baling capacity. A similar trend in results was reported by Nguyen *et al.*[22]

Table 3 — Energy equivalents of sources[7]

S. No.	Energy input sources	Unit energy
1	Man	1.96 $MJ \cdot h^{-1}$
2	Diesel	56.71 $MJ \cdot l^{-1}$
3	Electricity	11.93 $MJ \cdot h^{-1}$
4	Tractor	64.80 $MJ \cdot h^{-1}$
5	Machinery	62.70 $MJ \cdot h^{-1}$

Sharma and Chandel *et al.*[8] also reported that the density of bales increased from 1.12 to 4.22 $t \cdot h^{-1}$ when the hayrake was used after the operation of the stubble shaver. The density of bales obtained from different treatments ranged from 129.77 $kg \cdot m^{-3}$ to 213.97 $kg \cdot m^{-3}$. Authors[21] also reported the density of the field baler between 130–200 $kg \cdot m^{-3}$. The maximum density was obtained for T_4 (213.97 kg m^{-3}) followed by T_5 (177.66 $kg \cdot m^{-3}$), T_3 (137.51 $kg \cdot m^{-3}$), T_2 (135.04 $kg \cdot m^{-3}$), and T_1 (129.77 $kg \cdot m^{-3}$). Smaller particle size produces denser products.[23]

The length and weight of the bale in the field baler varied from 600 mm to 700 mm and 13 kg to 16 kg, respectively. Results observed were found similar for bale weight by field baler.[21] The height and weight of the bale for the stationary baler (Full-length straw) varied from 800 mm to 950 mm and 160 kg to 172 kg, respectively. The height and weight of the bale for the stationary baler (chopped straw) varied from 510 mm to 590 mm and 42 kg to 50 kg, respectively. The time requirement of different treatments ranged from 0.44 h to 2.09 h. The minimum time requirement was obtained for T_2 (0.44 h) followed by T_1 (0.69 h), T_4 (0.89 h), T_5 (2.06 h), and T_3 (2.09 h). The statistical

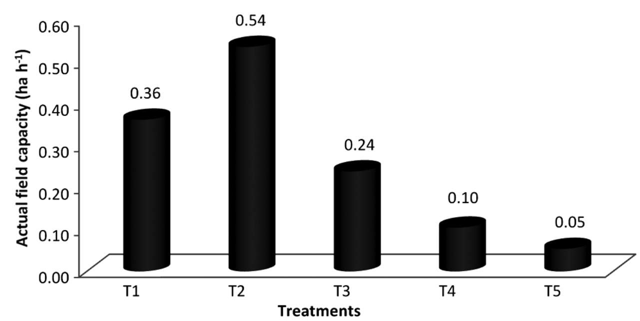

Fig. 1 — Field capacity of the treatments

analysis of data for time requirement indicated high significance amongst all the treatments except for T_2 & T_3 which were non-significant amongst themselves. The coefficient of variance was 3.84%. Moisture content, field capacity, bailing capacity, bulk density, and weight of bales are quality-related parameters of densified biomass because they affect storage, handling, transportation, and conversion which was also reported by Tumuluru and Wright [24].

Fuel / Electricity Consumption

The mean value of fuel and electricity consumption is given in Table 4. In treatment T_1 (Stubble shaver + tractor operated baler) 6.46 $l \cdot h^{-1}$ diesel was used, T_2 (Stubble shaver + hay rake + tractor operated baler) 10.2 $l \cdot h^{-1}$ diesel, T_3 (Field baler in stationary mode) 3.48 $l \cdot h^{-1}$, T_4 (Stationary baler for full straw densification) 1.65 $kW \cdot h^{-1}$ of electricity was consumed and T_5 (chaff cutter) used 4.01 $l \cdot h^{-1}$ of diesel and (Stationary baler for chopped straw) consumed 1.79 $kW \cdot h^{-1}$ electricity. The lowest diesel was consumed by T_5 and the highest by T_2. A similar trend of fuel consumption was found by Sandhya *et al.*[20], and Sharma & Chandel.[8] The increase in fuel and electricity consumption increases the cost of operation. The treatment T_2 included the operation of the hay rake before the operation of the field baler and thus has higher fuel consumption than T_1. Moreover, after the operation of the hay rake the straw load increased which increased the load on the tractor and thus increased fuel consumption. The treatment T_3 has lower fuel consumption than T_1 as the stubble shaver was not used in this field and the baler was stationary. Treatment T_5 recorded higher electricity consumption than T_4 due to the reason that higher pressure was needed to densify full-length straw than chopped straw.

Table 4 — Average fuel/electricity consumption of machinery

Treatments	Machinery operation	Fuel/Electricity consumption
T_1	Stubble shaver + tractor-operated baler, (Diesel, $l \cdot h^{-1}$)	6.46
T_2	Stubble shaver + hay rake + tractor-operated baler, (Diesel, $l \cdot h^{-1}$)	10.12
T_3	Field baler in stationary mode, (Diesel, $l \cdot h^{-1}$)	3.48
T_4	Stationary baler for full straw densification, (Electricity, $kW \cdot h^{-1}$)	1.65
T_5	Chaff cutter, (Diesel, $l \cdot h^{-1}$)	4.01
	Stationary baler for chopped straw densification, (Electricity, $kW \cdot h^{-1}$)	1.79

Man-hour Requirement

The total man-h requirement per tonne for baling operation and handling (gathering straw from the field and loading bales into the truck) operation for treatment T_1, T_2, T_3, T_4 and T_5 were 3.83, 3.57, 11.05, 7.85 and 13.39, respectively. The minimum man-h for baling a tonne of straw was obtained for T_2 (0.44) followed by T_1 (0.69), T_4 (5.32), T_3 (9.21), and T_5 (10.96). Mechanized operation reduced labour requirement by 90% also reported by Nguyen *et al.*[22] The minimum man-h for gathering and loading one tonne of straw was obtained for T_3 (1.84) followed by T_5 (2.43), T_4 (2.53), T_2 (3.13) and T_1 (3.14). The man-hour required per tonne of straw depends on the handling of straw, usage of machinery, tying operation of the bale, picking of bales from the field/ pushing of bale out of compression chamber in stationary baler, etc. The total man-hour required for baling was almost equal for T_1 (3.83) and T_2 (3.57). In T_2 an additional operation of hay rake was conducted but it reduced time and increased the efficiency of the baler. In treatment T_3 (11.05), a maximum man-hour was required for collecting straw from the field. In treatment T_4 (7.85) and T_5 (13.39) all the operation was done manually hence man-hour requirement increased. The man-hour requirement under different treatments is given in Fig. 2.

Energy

Energy requirements for different treatments ranged from 50.16 to 152.53 $MJ \cdot t^{-1}$. Minimum energy was required for T_4 (50.16 $MJ \cdot t^{-1}$) followed by T_2 (102.65 $MJ \cdot t^{-1}$), T_3 (117.57 $MJ \cdot t^{-1}$), T_4 (144.53 $MJ \cdot t^{-1}$), and T_5 (152.53 $MJ \cdot t^{-1}$). Data demonstrates that, despite total energy consumption being higher for baling without and with a rake as compared to the

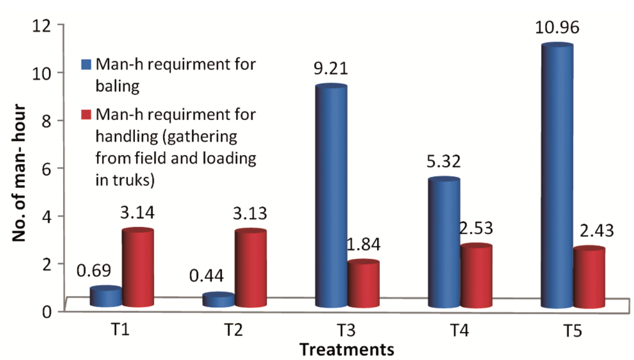

Fig. 2 — Man-hour requirement under different treatment

traditional approach, total time and total cost are lower. Similar results reported by Maski.[25] The statistical analysis of data on energy requirement was which were non-significant. The coefficient of variance was 3.01%. The detail of the treatment is given in Table 5.

The energy required depends on fuel and electricity consumption, man-hour requirement, and type of machine required to perform the different treatments. The energy required for producing bale was minimum for T_4 (50.16 MJ·t^{-1}) because it required very less electricity. Treatment T_4 was followed by treatment T_2 (102.65 MJ·t^{-1}) as it required the lowest man-hour and also less fuel energy than the treatment T_1 also same trend of energy consumption was reported by Parveen *et al.*[26] Energy required depends on fuel and electricity consumption, man-hour requirement, type of machine required to perform the different treatment. The energy required for producing bale was minimum for T_4 (50.16 MJ·t^{-1}) because it required very less electricity. The energy required depends on fuel and electricity consumption, man-hour requirement, and type of machine required to perform the different treatments. The energy required for producing bale was minimum for T_4 (50.16 MJ·t^{-1}) because it required very less electricity. Treatment T_4 was followed by treatment T_2 (102.65 MJ·t^{-1}) as it required the lowest man-hour and also less fuel energy than treatment T_1. The treatment T_3 (117.57 MJ·t^{-1}) required higher energy than T_2 (102.65 MJ·t^{-1}) because more energy was required for straw collection from the field. The maximum energy was required by treatment T_5 (152.53 MJ·t^{-1}) for making a bale of one tonne of straw because it required more human-hour and there was higher electricity consumption. The results reported by Maski[25] for baling with and without hay rake had the same trend as for treatments T_1 and T_2.

Energy Distribution

Percent energy consumed by various sources like humans, diesel, electricity, tractor, and machinery was calculated for each treatment. The percent energy consumption by humans, diesel, electricity, tractor, and machineries for T_1 was 1, 83, 0, 7, and 9, for T_2 - 1, 88, 0, 6, and 5, for T_3 - 15, 72, 0, 5, and 8, for T_4 - 21, 0, 35, 0, and 44, and for T_5 -14, 49, 24, 3, and 10, respectively as shown in Fig. 3. Similar energy distribution trends in percentage have been represented by researcher Nguyen *et al.* [22] and Pradhan *et al.*[27]

Table 5 — Treatment mean of energy requirement

Treatment name	Energy requirement
T_1	144.53^B
T_2	102.65^D
T_3	117.57^C
T_4	50.16^E
T_5	152.53^A
General mean	110.72
p-value	<.0001
CV (%)	3.01
C.D.	5.31

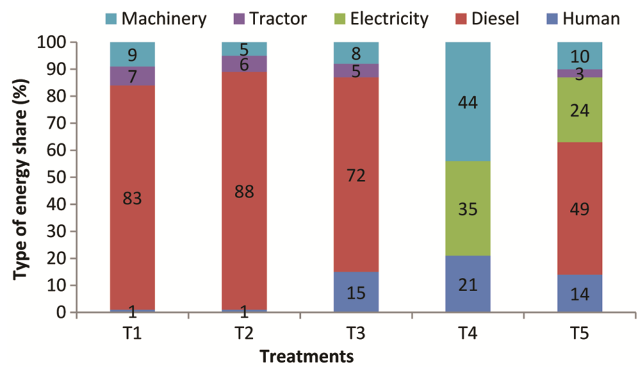

Fig. 3 — Energy percentage share under different treatments

Conclusion

It was concluded that treatment T_3 can be used in waterlogged areas. In the case of manual harvesting and less land holding the treatment T_4 was found better. The treatment T_5 was found most suitable for chopped straw densification. Treatment T_2 was found most appropriate while considering field capacity (0.54 ha·h^{-1}), bailing capacity (4.43 t·h^{-1}), and volume compaction ratio (5.26), whereas man hour time requirement for straw handling and bailing (3.57 man-h·t^{-1}) and consume 102.65 MJ·t^{-1} energy.

The study was limited to densifying paddy straw, important factors such as moisture content, cost-effectiveness, and usage of densified straw, etc. were not considered in the present research. Further research should be investigated by considering the above-discussed factors. This would increase the quality of densified straw such as strength, durability, density, nutrition (for animal feed), and calorific value (for fuel). Hence, the present study facilitates farmers to choose the best method of densification out of selected paddy straw densification processes.

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