Mechanized urea spraying system for balers to enhance the nutritional quality of straw: a step to prevent straw burning

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A large portion of unused crop residues is burnt in the fields primarily to clear the left-over straw and stubbles after the combine harvest. Studies have reported several ill effects of crop-residue burning on soil organic carbon and fertility, including reduction in productivity in the long term, environmental pollution and human health. It also produces greenhouse gases causing global warming. Rice and wheat produce large amounts of residue in India. Non-availability of labour, the high cost of residue removal from the field and the increasing use of combines in harvesting the crops are the main reasons for burning crop residues in the fields. Rice straw is unsuitable animal feed due to its high silica content and wheat straw for due to its hard stem and difficulty chewing in unchopped form. Using supplements like urea and is feeding straw sprayed with urea improves its nutritive value and intake. We have developed a mechanized baler equipped with a urea spraying system for spraying urea during baling operations on crop residues (paddy or wheat straw) to enhance their nutritional value. The developed system was evaluated in combine a harvested wheat residue field and nutritional analysis was performed. The crude protein in untreated wheat straw increased from 3.68% to 10.10% after urea treatment. The metabolizable energy was also found to improve by 3% compared to untreated straw. Thus, urea-treated bales have potential use in dairy farming.

Keywords: Combine harvest, crop residues, mechanized straw baler, nutritional value, urea treatment.

BURNING of crop residues is considered a cost-effective way of removing stubble. In India, more than 683 million tonnes (mt) of different crop residues are produced, of which a major part is used as fodder, fuel in various industrial processes as energy and in paper production. Despite this, about 178 mt of surplus crop residues are available around the country. During 1960–1961, rice and wheat production was reported as 34.6 and 11 mt respectively, which is expected to rise to 122.3 and 109.5 mt respectively, during 2020–2021 (refs 1–3). A large portion of unused crop residues is burnt in the fields primarily to clear the leftover straw and stubbles after harvest. An estimated 87 mt of surplus crop residues is burnt are different croplands[4–7]. The air pollution emission intensity of different crop residues also varies. For example, the particulate matter ($PM_{2.5}$) emission (g/kg) from the burning of different types of crop residues follows the order: sugarcane (12.0) > maize (11.2) > cotton (9.8) > rice (9.3) > wheat (8.5)[5]. Crop residue burning also emits SO_x, NO_x, NH_3, and volatile organic compounds (VOCs), which are precursors for forming particulates in the atmosphere[8]. It has been estimated that more than 8.5 mt of carbon monoxide is emitted into the atmosphere while burning crop residues. Studies have also reported several ill effects of crop residue burning on soil organic carbon and fertility, including a reduction in productivity in the long term[9]. It is estimated that burning of crop residues *in situ* releases about 627 kilotonnes (kt) of particulate matter (PM_{10}) and 4677 kt of carbon monoxide into the atmosphere annually in India[5]. Rice and wheat produce large amounts of residue in the country. Non-availability of labour, high cost of residue removal from the field and increasing use of combines in harvesting crops are the main reasons for burning crop residues in the fields. In the rice–wheat system, 34% of the residue comes from rice and 22% from wheat crops, most of which is burnt on-farm[10]. Burning of crop residues causes environmental pollution, is hazardous to human health, produces greenhouse gases causing global warming and results in loss of plant nutrients like N, P, K and S. Therefore, appropriate management of crop residues is necessary[11,12].

In India, crop residues are traditionally utilized as animal feed or by supplementing them with some additives. However, crop residues being unpalatable and low in digestibility, cannot form the sole feed for livestock[13]. Rice straw is poor cattle feed due to the high content of silica in rice, so its straw management is a challenge. Also, wheat straw in unchopped form is not fed to livestock. It is also not preferred by the animals as the stem is hard and is difficult to chew[12,14]. Therefore, there is a need for residue management systems with good potential for resource use efficiency[15,16]. To meet the nutritional requirements of animals, the residues need processing and enriching with urea and

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molasses[17,18]. As such, supplements like urea, oil cakes or green leaves should improve the intake of crop residues by providing a more favourable rumen environment. For example, feeding straws sprayed with urea improves their intake, just enough for the maintenance of animals. Urea treatment of straw has been carried out using a sprayer on the wheat thresher and dripping methods on stack of bales[19–22]. The treatment of straw by urea increased its nitrogen content, enhanced palatability, digestibility, nutrient uptake, and improved animal growth and milk yield, consequently increasing the feed value[23–25]. Machine-based residue incorporation with the help of a microbial spray or baling of residue for animal feeding may be a useful option for better carbon sequestration, soil carbon stock and low global warming potential[12]. Therefore, we have developed a baler equipped with a urea spraying system for paddy and wheat straw during baling operations to enhance the nutritional value of crop residues.

Materials and methods

Design of mechanized urea spraying

The urea spraying system was developed based on field observation data and the standard application rate of urea treatment. The main components used in this system are solution tank, flat fan nozzles, pump, strainer, cut-off valve, oil-type pressure gauge, boom arm, belt and pulley. The belt and pulley were chosen based on the required revolutions per minute (rpm) to operate the HTP pump with the help of a baler flywheel through tractor power take off (PTO) power. The baler was attached to the tractor with the help of a drawbar hitch. The flywheel of baler was connected with the tractor's PTO for rotational power with the help universal joint and telescopic shaft. The urea solution tank was mounted on the top of the baler. A frame of mild steel (MS) flat and MS angle iron was used to fabricate the supporting frame of the tank. The MS flat of 50 × 5 mm and angle iron of 50 × 50 × 5 mm size were selected to fabricate a frame of 1200 × 520 mm to mount the tank. The tank was fixed in a horizontal position on the baler with four vertical column supports of 670 mm height. The tank was rigidly fixed to the frame with the help of two semi-circular rings, nuts and bolts. The rings were made of MS flat (50 × 5 mm) of 570 mm diameter. Figure 1 shows the CAD drawing of the developed urea spraying system.

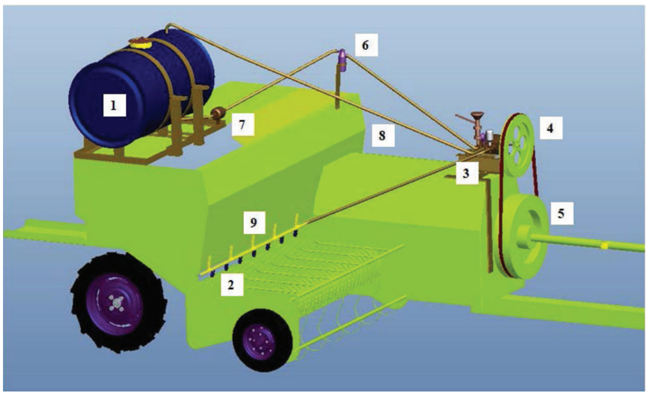

Figure 1. CAD view of the developed mechanized urea spraying system. (1) Urea solution tank; (2) flat fan nozzles; (3) HTP pump assembly; (4) belt and pulley; (5) fly wheel; (6) strainer; (7) cut-off valve; (8) pipe; (9) boom arm.

Components of urea spraying system

Nozzles: The flat fan nozzles of 2.1 lpm discharge at 3.5 bar pressure were used to spray urea solution on the loose straw while carrying it from the reel to the compression chamber. A boom of 1650 mm in length was used and seven nozzles were fitted at 220 mm intervals. Filters were used to prevent the nozzle orifice from clogging.

Pump: A HTP pump (ASPEE, India), three pistons, 36 lpm discharge and 2.24 kW power requirement was used to spray urea solution at high pressure. It was capable of delivering liquid at a maximum pressure of 400 psi. The shaft of the pump was connected with the belt pulley arrangement for its rotational motion through a tractor PTO. The pump assembly consisted of an oil-type pressure gauge, pressure regulator valve, suction, delivery and agitator lines. The pressure-regulating valve was used to control the discharge rate according to the requirement.

Urea solution supply line: It consisted of a suction line made of 40 mm diameter flexible plastic pipe (HDP), and a delivery line of flexible plastic pipes and PVC pipes of 20 mm diameter. The suction line receives the urea solution from a storage tank, while the delivery line supplies it to the liquid applicator nozzle unit.

Storage tank: Urea solution tank of 420 l capacity made with high-density plastic was used. The fluid control system mounted over the tank consisted of on–off valves, viz. suction, delivery, by-pass hose with pump control and agitator hose. For ease handling and to prevent the corrosion, a plastic storage tank of 420 l capacity was used to store water/urea solution for supply to the pump.

By-pass line: A by-pass line made of a flexible pipe of 40 mm diameter was used to bypass the excess flow of urea solution. A part of the liquid delivered by the piston pump was utilized by the treatment unit and the remaining liquid was diverted back to the storage tank through the flexible by-pass line. This provision helped in avoiding wastage of liquid as well as regulation of operating liquid pressure to liquid urea applicator for obtaining variable discharge rates.

Control valve: The variable discharge rate of the nozzles was obtained by supplying liquid to the liquid applicator at different operating pressures by regulating the liquid inflow rate to the treatment straw. For this, control valves were fitted in the pump.

Screen filter: A screen filter was used to remove solid impurities like fine sand, dust, etc. from the solution to prevent the clogging of nozzles. The filter could be reused after cleaning.

Pressure gauge: The pressure at which urea solution was being supplied to the treatment unit was monitored using a pressure gauge. This indicates liquid pressure varying from 0 to 14 kg/cm^2 with a least count of 0.1 kg/cm^2. In the present case, the pressure was varied from 1.5 to 14 kg/cm^2.

Calibration of nozzles

The calibration of nozzles was carried out at different pressures. Seven nozzles were attached to maintain moisture content and uniformity. The nozzles were calibrated at different pressures for varying nozzle discharge rates. The system consisted of flat fan nozzles, pump, tank, etc. The pump was operated at 820 rpm with tractor PTO. The pump was operated at different pressures and the corresponding nozzle discharge was measured using a measuring cylinder. The uniformity test of nozzles was carried out on a patternator at different pressure ranges. In this way, all nozzles on the boom were tested. Figure 2 shows the calibration set-up.

Performance evaluation of urea spraying system and nutritional analysis

The field evaluation of urea spraying system was carried out for wheat straw. The tractor speed was maintained at 2.5 km/h during the evaluation. The availability of loose straw per unit area was also calculated. The baler was operated in the wheat straw field initially and the average weight of dry bale (ten bales) was recorded. The amount of urea was then calculated by assuming the ratio of urea to straw dry matter (DM) (wt/wt), which is recommended for ammonia (urea) treatment. Urea solution was prepared as follows: 8 kg of granular urea was mixed with 100 l of water for 8% concentration, and a similar solution for 10% concentration level as well. Its concentration was maintained according to the capacity of the urea solution tank. During the performance evaluation of the urea treatment system, all the pipe connections were checked and the application rate was set to apply urea solution to the conveying width of the chamber. The liquid application rate was fixed according to the calibrated pressure and discharge rate relationship for wheat straw. The nozzles discharge rate was decided according to the time interval; weight and moisture content of bales. The baler was evaluated in the wheat-harvested field as follows. Urea concentrations of 8% and 10% were chosen to increase the moisture level by 50%, 60% and 70%. The speed of operation was 2.5 km/h. The samples were collected from different combinations of urea concentration (UC) and moisture level (ML) in terms of treatment T_1 (8%, 50%), T_2 (8%, 60%), T_3 (8%, 70%), T_4 (10%, 50%), T_5 (10%, 60%) and T_6 (10%, 70%) and packed in airtight bags. The treated urea solution was subjected to nutritional analysis according to the standard method. Figure 3 shows the field evaluation of the urea spraying system.

After completion of urea spraying, the weight of each urea-treated bale was recorded to determine the amount of moisture retained by it, which was found as the difference between the weight of the bale before and after treatment. The urea-treated individual bales were wrapped airtight polyethylene sheet, stacked and stored in shade at room temperature for a curing period of 21 days. Dry and urea-treated bale samples were also kept in the oven to determine the moisture content. During this period, the bale weight was taken at an interval of five days and variation in weight was recorded. The weight of bales was recorded to determine the variations in moisture content during the curing period.

Urea-treated and untreated wheat straw samples were sent to ICAR-National Institute of Animal Nutrition and Physiology (NIANP), Bengaluru, for nutritional analysis. The standard method was followed for the nutritional analysis of straw. Crude protein (CP), total ash, neutral detergent fibre (NDF), acid detergent fibre (ADF), dry matter digestibility (DMD), organic matter digestibility (OMD) and metabolizable energy (ME) were analysed keeping in view the nutritional quality and feed safety. The straw samples were subjected to nutritional analysis for CP, total ash[26] and NDF and ADF[27]. *In vitro* gas production test was conducted on the samples to determine *in vitro* dry matter digestibility (IVDMD) and *in vitro* organic matter digestibility (IVOMD).

CP estimation is a tedious and time-consuming process; therefore, an automatic nitrogen analyser system was used to save both chemicals and time. It is based on the Kjeldahl method, which involves digestion of the sample

Figure 2. Calibration of urea spraying nozzles on a patternator.

Figure 3. ***a***, Field evaluation of urea spraying system. ***b***, Storage of urea-treated bales.

Table 1. Calibration of flat fan nozzles

Pressure (kg/cm^2)	Discharge (l/min)
1.5	12.24 (SE: ± 1.2)
3.5	14.10 (SE: ± 0.75)
7	17.34 (SE: ± 1.13)
9	19.19 (SE: ± 1.61)
14	23.81 (SE: ± 1.75)

in concentrated sulphuric acid with a catalyst. The CP was calculated using (eq. (1)).

$$\text{Crude protein } \% = \frac{Y \times (B - B_1) \times 0.0014 \times 6.25 \times 100}{X \times W}, \quad (1)$$

where Y is the volume (ml) of the digested sample, X the volume (ml) of the aliquot taken for distillation, B the volume (ml) of N/10 H_2SO_4 used for titration of sample, B_1 the volume (ml) of N/10 H_2SO_4 used for titration of blank distillate and W is the weight of oven-dried sample taken for digestion.

Results and discussion

Calibration of nozzles

The flat fan nozzle was calibrated in the laboratory to obtain a relationship between pressure and discharge rate. This was used to choose the pump pressure to control the discharge rate as well as the moisture content of dry matter of wheat straw. The actual discharge rate of each nozzle was calculated at five different pressures. The total liquid discharge with respect to the application rate and the number of nozzles gave the actual inflow rate of each nozzle. The pressure was selected as 1.5, 3.5, 7, 9 and 14 kg/cm^2. The actual discharge rate of the nozzles was found to be 12.24 (SE: ± 1.2), 14.10 (SE: ± 0.75), 17.34 (SE: ± 1.13), 19.19 (SE: ± 1.61) and 23.81 l/min (SE: ± 1.75) at a pressure of 1.5, 3.5, 7, 9 and 14 kg/cm^2 respectively. The calibration equation showed a linear relationship with R^2 of 1. Table 1 gives the calibration data.

Table 2. Field observation data of urea solution spraying system

Crop straw	Wheat
Moisture content of straw (% db)	9.4
Weight of loose straw (kg/m^2)	0.50
Weight of untreated bale (kg)	10.5
Average time taken in one bale (s)	46
Working capacity (bale/h)	80
Effective field capacity (ha/h)	0.27
Fuel consumption (l/h)	5. 5
Average weight of twine (g/bale)	8.5
Average weight of twine (kg/ha)	4.1
Average weight of polyethylene stretch roll (g/bale)	162
Average weight of polyethylene stretch roll (kg/ha)	77.8

Field evaluation of urea spraying system in wheat straw field

Mechanized urea solution spraying system was evaluated in a wheat straw field. A few basic field observation data were recorded. The average moisture content of wheat straw was 9.4% (db). The weight of loose wheat straw (straw load) was found to be 0.50 kg/m^2. The average time in making one bale was 46 sec. The average weight of twine was found to be 4.1 kg/ha for wheat straw. It was also observed that polyethylene stretch roll required for wheat bales was 162 g/bale. Table 2 shows the field observation data.

Effect of urea treatment on the weight of wheat straw bales

The weight of individual urea-treated wheat bales was found to vary from 15.26 to 15.35 kg (SE: ± 0.38 kg), 16.46 to 16.50 kg (SE: ± 0.21 kg) and 17.45 to 17.52 kg (SE: ± 0.17 kg) for moisture level of 50%, 60% and 70% respectively, at all concentration levels of wheat straw bales. The average retention efficiency was 91%. Table 3 shows the variation in the average weight of treated wheat bales.

Table 3. Variation in weight of treated wheat bales

Urea concentration	8%			10%		
Moisture level (ML)	50%	60%	70%	50%	60%	70%
Sample	Bale weight (kg)			Bale weight (kg)		
1	15.55	16.61	17.49	15.70	16.51	17.52
2	15.35	16.51	17.30	15.42	16.71	17.60
3	14.89	16.26	17.56	14.94	16.28	17.45
Average	15.26	16.46	17.45	15.35	16.50	17.52
SE (±)	0.33	0.18	0.13	0.38	0.21	0.17

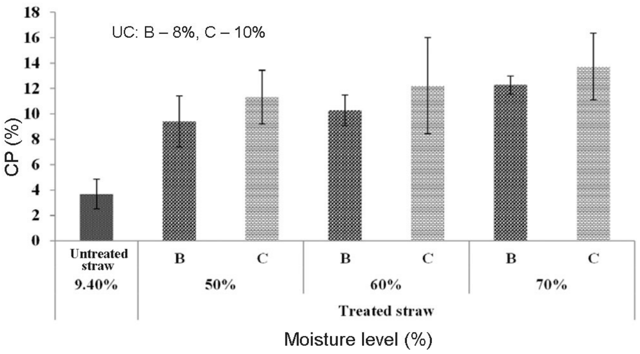

Figure 4. Effect of moisture level (ML) and urea concentration (UC) levels on crude protein (CP) of wheat straw.

Effect of urea treatment on the nutritional value of wheat straw bales

Wheat straw was nutritionally analysed at ICAR-NIANP. CP content of untreated wheat straw was found to be 3.68 ± 1.17. Due to the treatment of urea solution at all levels, the CP content had increased in all the treatments and ranged from 9.14% in treatment T_2 (8% UC and 60% moisture) to 13.41% in treatment T_6 (10% UC and 70% moisture). The total ash content ranged from 7.87% to 10.28% compared to 9.53% in untreated wheat straw. The results of one-way ANOVA indicated that variation in CP was found to be significantly dependent on UC level ($P < 0.001$). When MC was increased from 50% to 70%, CP was found to increase from 9.24% (SE: ± 0.71%) to 10.10% (SE: ± 0.44%) for 8% UC. Similarly, CP was found to be increase from 11.06% (SE: ± 0.75%) to 13.41% (SE: ± 2.40%) for 10% of UC (Figure 4).

The ash content of treated bales was found to vary from 7.87% (SE: ± 0.28%) to 10.28% (SE: ± 0.78%) in all the treatment levels of UC, while ash content in untreated wheat straw was 9.53% (SE: ± 1.02%). There was no clear trend in the case of ash content in treated wheat bales. DM decreased from 87.95% (SE: ± 2.70%) to 75.12% (SE: ± 4.94%) with an increase in moisture level from 50% to 70%, while DM of untreated straw was 93.10% (± 0.34%).

NDF content (%) of the treated samples was found to range from 71.91% (SE: ± 3.07) to 74.84% (SE: ± 1.16%) compared to 77.03% (SE: ± 2.58%) in untreated straw. There was a reducing trend in NDF in the samples with a higher level of urea treatment (beyond 5.6%). ADF content of treated baled straw was found to range from 43.49% (SE: ± 0.41) to 46.13% (SE: ± 0.70) compared to 46.53% (SE: ± 1.83) in untreated straw.

IVDMD was more in treatments T5 and T3 compared to treatment T2. It increased from 34.97% (SE: ± 2.56%) to 44.72% (SE: ± 1.60%) for 8% of UC and MC levels from 50% to 70%. Higher ME was found in treatment T5, followed by treatments T3, T4 and T6. Keeping in view the overall nutritional analysis, treating wheat straw at 8% UC and 70% moisture level would be more effective.

Gas production was found to vary from 20.66% (SE: ± 0.61%) to 27.33% (SE: ± 0.45%) for the entire range of tests for UC and ML. Results show that ME of urea to treated straw increased from 5.54 (SE: ± 0.08) to 6.22 MJ/kg (SE: ± 0.18) for UC of 8% for all test ranges of ML, while ME of untreated wheat straw was 5.77 MJ/kg (SE: ± 0.04).

Due to the optimum increase in CP, IVDMD and ME of treated straw, 8% UC with 70% moisture level can be recommended for wheat straw baling. As there is no information on residual urea in treated straw, higher levels were not recommended, keeping in view the toxicity of urea.

Economics of the developed system

The cost of the developed mechanized urea spraying system was estimated to evaluate its economic feasibility. The costs of tractor, paddy straw baler, urea spraying system, twine, polyethylene wrapping sheet and operator were considered for estimation. The cost economics was worked out by taking the quantity of wheat straw in the field as 5.5 tonne/ha. The cost of construction of the urea spraying system was approximately Rs 0.3 lakhs. The total cost of operation of the urea spraying system with baler and tractor was Rs 4000/ha. The cost of urea treatment of straw with the developed spraying system was Rs 0.50/kg of straw. The cost of untreated paddy and wheat straw baled in the market was Rs 12,000/tonne (ref. 28). Hence, the mechanized urea spraying system can generate additional income for the farmers.

Conclusion

The mechanized urea spraying system developed was used in a combine harvested field for spraying of urea solution on straw during baling operation. The system potentially improve the nutritional quality of straws such as CP, IVDMD, ME, etc. The effectiveness of the system depends on factors such as type of straw, urea concentration, moisture level, compaction, storage and environmental factors. Due to the optimum increase in CP, IVDMD and ME of treated straw, 8% UC with 50% ML has been recommended for wheat straw baling. The moisture content of treated bale ranged from 45.41% to 66.30% and its weight ranged from 15.26 to 17.52 kg for wheat straw. The cost of urea treatment of straw was Rs 0.50/kg and income generated from the treated bales was Rs 10,000/ha.

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