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Development of a Novel Helical-Ribbon Mixer Dryer for Conversion of Rural Slaughterhouse Wastes to an Organic Fertilizer and Implications in the Rural Circular Economy

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Abstract: Organic wastes of rural slaughterhouses in developing countries comprise of blood and undigested rumen contents harboring infectious microbial pathogens and having impermissible BOD_5 and COD values. Previously we demonstrated valorization of blood and rumen contents through drying and conversion to an efficacious organic fertilizer which was free from infectious pathogens and heavy metals. Here we describe fabrication of a novel helical-ribbon mixer dryer for transition from the current small-scale household cooking to equipment-driven sustainable production. Blood and rumen digesta mixed in a 3:1 ratio, having initial moisture of 85%, were dried at 90–110 °C for 3–4 h to attain 15.6% final moisture-containing organic fertilizer. Energy consumption and moisture extraction rate were 49.4 MJ per batch and 18.9 kg h^{-1} respectively. Using this method, small abattoir owners could emerge as multi-product producers to enhance earnings while farmers could source the fertilizer locally for organic farming. The two activities can be complementary to each other and become a sustainable circular economy model. We applied a spreadsheet-based model for calculation of cash flow, breakeven point and conducted financial cost–benefit analysis on the projected operation of the dryer. Fertilizer production parallel with the meat trade should be profitable for slaughterhouse owners and farmers apart from generating local employment opportunities.

Keywords: abattoir waste; circular economy; organic fertilizer; sustainable development goal; dryer fabrication

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1. Introduction

Organic wastes generated in rural slaughterhouses of developing countries are discarded without any treatment due to desuetude of cost-effective recycling processes. Landfilling is generally practiced for the disposal of slaughterhouse waste in developing countries because of the operative easiness and low management cost [1]. Landfills release toxic compounds, leachate and gases directly to the surrounding environment [2]. Higher emissions of carbon dioxide, nitrous oxide and methane turn landfills into anthropogenic contributors to climate change [3]. Moreover, beneficial microbial communities present in soil are negatively affected due to land application of raw organic waste [4]. Rural slaughterhouses receive all types of livestock, including diseased animals, because no screening for healthy/diseased is carried out. Further, these abattoirs are the terminal station for disease-infected unproductive animals [5]. Several infectious pathogens are present in slaughterhouse waste that are capable of transmitting diseases to both humans and animals [6,7]. Swine influenza and H1N1 influenza were reported among poultry farm workers [8,9]. An estimated 16–19% of slaughterhouse personnel were affected by anthrax, tetanus, malaria and typhoid like diseases in abattoirs of Western Kenya [10]. Therefore, inactivation of pathogens is required for various value-added applications of slaughterhouse wastes.

Diverse techniques for the treatment of slaughterhouse waste, including rendering, anaerobic digestion, acid or alkaline hydrolysis, enzymatic treatment and composting have been adopted [1,6,7]. Rendering of solid slaughterhouse waste was used to produce animal feed and low-quality organic fertilizer [11]. Slaughterhouse waste can be used as good feedstock for anaerobic digestion due to its high methane yields [12]. The digested by-products are effective in agricultural applications [13]. The processes of alkaline or acid hydrolysis and enzymatic treatment are relatively new. Survival of viruses is observed in mesophilic aerobic digestion and removal of these in thermophilic digestion is also not assured. So, additional heat treatment of the feedstock and pasteurization at 70 °C/60 min should be performed before land application [6]. Other than composting, the said methods are too expensive and complicated to be implemented in rural slaughterhouses of developing countries because of their economic and legal restrictions [14]. Composting results in destabilized and contaminated organic matter, thus making compost a pathogen source [15]. Furthermore, loss of nitrogen due to ammonia volatilization depletes the nutritional value of the fertilizer produced [16]. The need for scientific management of rural slaughterhouse wastes in India and other similar developing economies has been reiterated by international agencies such as the Food and Agricultural Organization [17], the World Health Organization [18] and the World Bank [19]. A cost-effective recycling system is thus a strong proposition. Slaughterhouse waste is highly nutrient rich, recyclable and applicable for the conservation of soil health [20]. Such a type of animal-derived organic waste is typically non-homogeneous in composition, contains large amounts of organic matter, but propagates faster proliferation of pathogens [21]. Adequate treatment improves the physical and chemical properties of the abattoir waste, reduces pathogens and phytotoxicity and minimizes odor without losing its nutrient value [5,22].

India has the largest total population of livestock in the world [23]. According to the USDA "Livestock and Poultry: World Markets and Trade" report, India is the fourth-largest producer and domestic consumer of beef in the world [24]. Approximately 32,000 informal slaughterhouses exist in India [25], while the country has only 3600 legal slaughterhouses [26]. Cattle blood and rumen matter are the only by-products of annihilation that have no monetary value in rural slaughterhouses [23]. It is a common practice of rural abattoirs to openly dump these wastes onto nearby land, and into sewer systems and water bodies [27]. Treatment methodologies followed in developed countries demand huge investment [28] and are therefore impractical for implementation in small-scale and scattered abattoirs situated in rural areas of developing countries.

A low-cost recycling technology for blood and rumen digesta was established by Roy et al. [14], where small-scale cook-drying of bovine blood and rumen digesta transformed the wastes to an organic fertilizer named "bovine-blood-rumen digesta mixture" (BBRDM), which could be applied in agronomical practice. Very recently, Sankar et al. [23] developed rumen content-blood-coir pith (RBC) mixture which was formed into briquettes and applied in the pot cultivation of okra (*Abelmoschus esculentus*). Bhunia et al. [29] found zinc, manganese, boron, copper and iron abundant in BBRDM along with NPK. During the field cultivation of tomatoes in India, application of this nitrogen-rich organic fertilizer showed higher productivity and better characteristics of fruits compared to chemical supplementation [26]. Additionally, vegetables grown in BBRDM-fertilized soil were found to be safe for consumption because it contained acceptable limits of heavy metals, nitrite and nitrate. High nutrition value of BBRDM-grown vegetables was ensured along with non-toxicity and non-carcinogenicity of the vegetables [27]. However, the production of BBRDM is currently limited to small-scale household cooking process by the slaughterhouse owners.

Transition from the current small-scale household cooking process to an innovative technology driven commercial scale manufacturing is essential to address the local societal demand for an economically feasible technological solution to the waste-disposal problem and to develop a business model where abattoir owners set up organic fertilizer manufacturing units utilizing slaughterhouse wastes as raw materials, thus advocating the principles of circular economy. Bhunia et al. [20] demonstrated the benefits to meat producing industries, livestock owners and local farmers of adopting the concept of waste valorization and circular economy. Very recently, the critical success and risk factors of eco-innovative business models that promote a shift towards circular economy through agricultural waste valorization were described by Donner et al. [30] for the first time. Therefore, the present work is timely and appropriate. Practice of circular economy principles such as reduce, recycle, reuse, repair, redesign and remanufacture are directly aligned with attaining Sustainable Development Goal (SDG) 12 (Sustainable Production and Consumption) by utilizing new technologies and business models, lessening the quantity of unsustainable products that are produced and bought, sharing and repairing, converting waste to useful products and securely managing toxic substances. Consequently, resource efficiency can be enhanced and the pressure lowered on the natural environment. Additionally, circular economy can facilitate the achievement of many other SDG targets too. In effect, by realizing SDG 12, advancement on climate mitigation and environmental goals such as SDG 14 (Life Below Water) and SDG 15 (Life on Land) can be accomplished too [31]. Our objective is to propose a novel drying process through a technology design which would be attractive and useful to the rural slaughterhouses for conversion of the waste blood and rumen digesta to a pathogen-free organic fertilizer having low moisture content. The dryer performance was also determined under different heating conditions. We further estimated the earnings of the slaughterhouse owners (in monetary terms) within a business model where abattoir owners adopt this new waste recycling process and as entrepreneurs set up BBRDM manufacturing units. Estimation of the possible selling price of BBRDM vis-à-vis competing substitutes and assessment of social acceptance of the new fertilizer (BBRDM) by the farmers was also carried out.

2. Materials and Methods

2.1. Raw Material Characterization

The raw materials were waste blood and undigested rumen contents. The pH was measured following electrometry, and total solids (TS) by calculating the difference between the weights of raw material before and after bone drying at 105 °C for 24 h. Total suspended solids (TSS) were measured by filtration and drying. Biological oxygen demand (BOD_5), chemical oxygen demand (COD) and concentrations of oil and grease were determined following Roy et al. [14].

2.2. Parameters Measured for Dryer Fabrication

The specifications of the equipment were estimated based on physical parameters of bovine blood and rumen content and the end product of the processing. Moisture content on wet and dry basis was measured by convective drying in a hot air oven at 105 °C till constant mass was obtained. The feed rate of raw materials was determined by weight, while bulk density of blood, rumen content and the dried product were evaluated following the ASTM D7263 active standard [32]. The particle size of the dried product was calculated using laboratory scale sieving screens of mesh size ranging from 2 mm to 2 µm.

2.3. Process and Equipment Description

Blood and rumen content were collected immediately after the slaying of bovine animals. Every batch was fed with a mixture of three parts of cattle blood and one part of rumen digestive material by weight, followed by the drying operation at 90–110 °C until a uniformly dried product having the required level of moisture was achieved. All the sections of the machine and its operation are represented in isometric view (Figure 1), while Figure S1 is a photograph of the actual equipment under operation, also shown in Supplementary Video S1. The fabricated dryer comprised of three parts (Figure 1). First, the mixing and drying vessel (8) was made of stainless steel (SS 304 grade). Vessel specifications: diameter 0.61 m and height 0.71 m, having one closed end and being open on top. The vessel was mounted on a movable cart (7), which was fitted with a sliding plate and locking arrangement for convenient movement and handling which was in turn attached to the main frame (5) of the equipment. The movable cart was fitted with four castor wheels (10) that easily slid on the rails (9). Second, the mixing blade (11) was helical-ribbon shaped with sharp edges and concentric turns having ribbon width 0.58 m from the centre of axis. The length of the axis was 0.70 m for ensuring uniform mixing and equal distribution of heat throughout the operation. This mixing blade was attached to a spindle (4) that operated on a 2 HP motor (1) through coupling (3) and was electrically driven. The whole arrangement of mixing blade and the motor was further assembled with a manual screw jack (6) with an attached hand wheel (12) for easy vertical movement of the mixing blade inside the drum. Forward and reverse rotation of the mixing blade was maintained at 50–250 rpm. A monitoring panel for regulating the helical ribbon within the drying vessel was provided; the rotation per minute of the spindle was controlled from this panel. The panel also displayed the current (ampere) along with voltage (volts) during operation. Third, the heat source was a burner (13) using diesel and liquefied petroleum gas (LPG) that easily slid below the feed vessel. The burner supplied heat to the raw material, maintaining the temperature up to 90–110 °C for 3–4 h. A patent has been obtained in India by Bhowmik et al. [33] (patent number 370569) on the proposed dryer. Please see Supplementary Materials for the certificate.

2.4. Moisture Removal, Drying Time and Energy Consumption of the Drying Process

Specific energy consumption during each drying treatment—namely sun drying, cook drying, tray drying and drying in the new fabricated dryer with diesel and LPG as fuel—was calculated in terms of the involved drying time and energy utilized. The calorific value of diesel, LPG and wood were 42.2 MJ kg^{-1}, 45.8 MJ kg^{-1} and 17.5 MJ kg^{-1} respectively [34–36]. The energy required for water removal (MJ kg^{-1} of water) was used as one of the evaluating factors of the proposed drying process. The equipment fabricated was kept very modest for the ease of rural slaughterhouse implementation. The drying process simply involved removal of water from the system, leaving behind the dried material, as no solids were lost and weight of solids remained constant. The whole process of drying carried out in the equipment did not involve any hot air flow. Three batches were considered for calculating production (per day).

2.5. Performance Evaluation of the Fabricated Dryer

Two parameters, (a) specific moisture extraction rate (*SMER*) and (b) moisture extraction rate (*MER*), were determined according to Pal and Khan [37]:

$$SMER = \frac{Amount\ of\ water\ evaporated\ from\ the\ product}{Total\ energy\ input\ for\ drying} \tag{1}$$

$$MER = \frac{Amount\ of\ water\ evaporated\ from\ the\ product}{Total\ drying\ time} \tag{2}$$

Additionally, drying time and energy consumption were considered to be important. The drying rate equation [38] used for obtaining drying curves was:

$$N = -\frac{W_S}{A} \cdot \frac{dX}{dt} \tag{3}$$

where N is the drying rate, W_s is dried solid mass, A is drying surface area and X is the % moisture content.

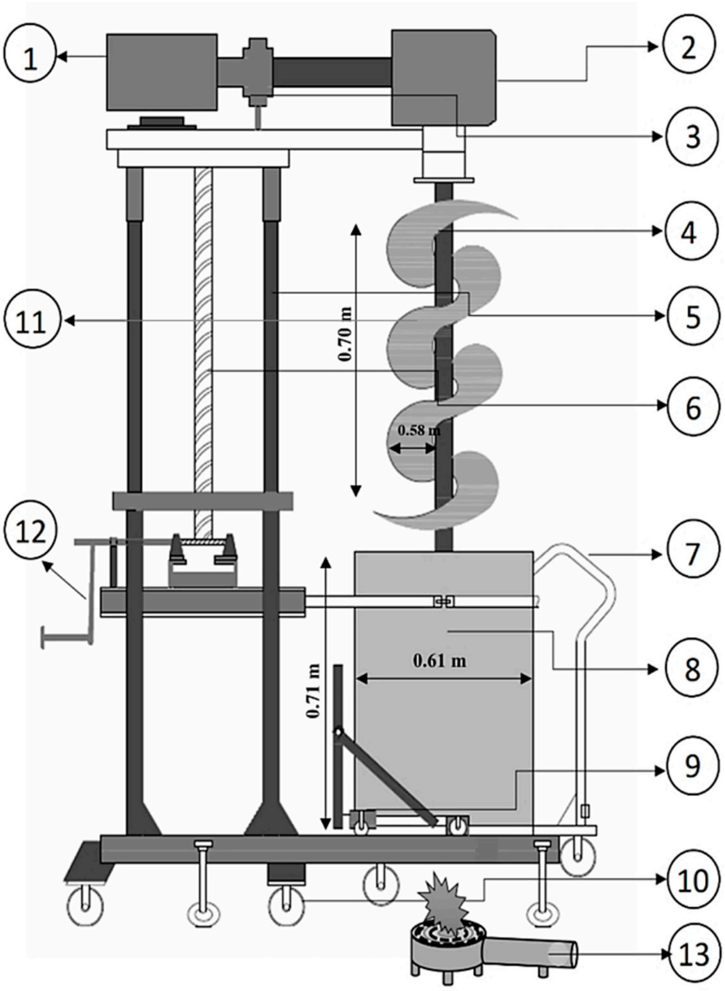

Figure 1. Isometric view of whole drying equipment with raised up mixing spindle before loading. (1) 2 HP motor, (2) gearbox, (3) coupling of motor and spindle, (4) mixing spindle, (5) main support system of the equipment, (6) screw jack lever, (7) mobile cart, (8) drying and mixing drum, (9) rail for drum wheel, (10) castor wheels, (11) helical mixing blade, (12) hand wheel handle for spindle operation, and (13) burner fueled by LPG.

2.6. *Performance Study of Previously Used Methods for BBRDM Production*

Evaluation of methods used earlier, namely sun drying, cook-drying and tray drying, was based on final moisture content achieved, total energy consumed and time taken for production. In the process of sun drying, the mixture of bovine blood and rumen digesta was boiled for approximately 90 min followed by sun drying for three successive days [14]. The raw waste after boiling was spread over 9.2 m^2 area for exposure to solar radiation. In the cook-drying method, the mixture was boiled in a metallic container over a wood-fired oven for about 5–6 h. Energy consumption calculations were based on the calorific value of wood as fuel. A ten-tray modeled dryer, each tray having a surface area of 0.768 m^2, was also used for production of BBRDM. The drying was carried out for about 9–10 h [29]. Energy consumption and moisture content of the final product were calculated as mentioned previously.

2.7. *Experimental Drying Curves of Drying Process in Fabricated Drying Unit*

Four drying curves were used for evaluation of the drying process. A drying curve where moisture content on a wet basis (%) was plotted versus time, a drying rate curve where drying rate was represented against time, a Krischer curve, a time-independent curve where drying rate was indicated against wet-basis moisture content and finally % moisture removed, was plotted versus time. These curves were applied to determine performance of the novel recycling unit and compare drying time with previously used methods of BBRDM production.

2.8. Preparation of a Sustainable Business Case for In Situ BBRDM Production

We ensured the acceptability of the product by the local farmers through trust building and exposing the farmers to the scientific rigor with which the new product was developed. We also considered fruitful adoption of the new dryer by the slaughterhouse owners and if it would make economic sense to produce BBRDM for the market.

2.8.1. Assessment of End-User Readiness

One hundred farmers living around the slaughterhouses of Magrahat II block, South 24 Parganas of West Bengal, India were identified and invited to a stakeholder consultation workshop organized by the School of Environmental Studies, Jadavpur University, India. The scientific results of our research work were communicated to this focused group. A survey questionnaire sheet of a total 22 questions was prepared in the local language (Bengali) for documenting prevailing agriculture practice and socioeconomic profiles of the targeted farmers. The survey questionnaire contained 18 multiple choice questions about their primary and secondary occupation, annual frequency of cultivation, agricultural produce, type of cultivation practices, land size ownership pattern, types of fertilizer and pesticides they applied along with their experiences of using chemical and organic fertilizer on their land. Four questions were about the amount of fertilizer and investment required for a specific size of land. They further responded to a few structured questions related to their preferences for application of BBRDM after they were provided the scientific facts.

2.8.2. Assessment of Supply Sector Readiness

The current business model envisages BBRDM production concomitant with the slaughterhouse meat trade. On average 20 buffaloes are slaughtered daily in one abattoir; almost 20 L of blood and 20 kg of rumen digesta are generated from one buffalo. Therefore, it is expected that 400 L of blood and 400 kg of rumen digesta will be available daily as raw material. In the present investigation, raw blood (approx. 60 kg) was mixed with rumen digesta (approx. 20 kg) in each batch. Considering the amount of waste generation, the novel helical-ribbon mixer dryer was operated with minimum load capacity of 90 kg. The load capacity could be eventually increased according to the escalation of demand for waste-recycled nitrogen-rich organic fertilizer in the market. One skilled laborer will be required for the operation of the equipment along with a manager who will be responsible for overall supervision of the works, maintenance of inventory and sales. Operation and maintenance costs will include purchase of LPG fuel, drums, buckets, shovels, plastic bags, oven gloves and safety equipment as well as spare parts of equipment. If the recycling unit is run for twelve hours a day and the raw materials are utilized in a 3:1 ratio (blood: rumen digesta), 60 kg of the product can be obtained daily. We applied a spreadsheet-based model for calculation of cash flow, breakeven point and to conduct financial cost–benefit analysis to ensure the feasibility of the proposed recycling unit.

3. Results and Discussion

3.1. Waste Characterization

The pH, TS, TSS, BOD_5, COD and concentrations of oil and grease of blood were measured to be 8.1 ± 0.2, 821,517 ± 1835 mg L^{-1}, 409,737 ± 1379 mg L^{-1}, 66,011 ± 2868 mg L^{-1}, 270,403 ± 1276 mg L^{-1} and 25 ± 1 mg L^{-1}, respectively (n = 6). The same parameters for rumen digesta were 8.0 ± 0.2, 57,220 ± 922 mg L^{-1}, 44,072 ± 578 mg L^{-1}, 140 ± 27 mg L^{-1}, 35,997 ± 131 mg L^{-1} and 76,992.33 ± 887 mg L^{-1} respectively (n = 6). The values of the measured parameters were beyond the permissible limits (for BOD 30 mg L^{-1}, COD 250 mg L^{-1}, oil and grease concentration 10–20 mg L^{-1}, TSS 100 mg L^{-1} and pH 5.5–9.0) prescribed in the environmental standards issued by the Ministry of Environment, Forest and Climate Change, Government of India, The Environmental Protection Act (of India), 1986 and Rules 1986. Table 1 represents abattoir waste and effluent characteristics.

Table 1. Characterization of bovine blood and rumen digesta as feedstock material.

			Waste Type	
		Permissible Values (as of EPA, 1986)	**Bovine Blood**	**Rumen Content**
Waste parameters	pH	5.5–9.0	8.1	8.0
	TS (mg L^{-1})	-	821,517	57,220
	TSS (mg L^{-1})	100	409,737	44,072
	BOD_5 (mg L^{-1})	30	66,011	140
	COD (mg L^{-1})	250	270,403	35,997
	Oil and grease (mg L^{-1})	10–20	25	76,992

3.2. Waste Recycling through the Drying Process

About 60 kg bovine blood and 20 kg rumen digesta were utilized as feed to produce an average 13.8 kg of BBRDM dried at 90–110 °C for 3.5 h with LPG. Moisture content of the feed on a wet basis was 85% and on a dry basis was 583%, indicating that the presence of water was 5.8 times greater than that of solids. Bulk densities of cattle blood and rumen digesta were 1160 kg m^{-3} and 923 kg m^{-3}, respectively. The density of raw material mix in the feed was 1142 ± 7 kg m^{-3}. The duration of drying to reach desired moisture content was about 4.5–5 h when diesel was used as fuel source.

Our process raises fewer concerns regarding pathogen survival. Roy et al. [27] from our group did not find *E. coli* O157:H7, *Mycobacterium*, *Clostridium*, *Salmonella*, *Bacillus*, *Brucella* or fecal coliforms through traditional plating and incubation techniques in BBRDM as the final product. Recently, Bhunia et al. [29], also from our group, confirmed the absence of major slaughterhouse pathogens as defined by Franke-Whittle and Insam [6] in BBRDM-fertilized soils through the 16S rRNA metagenomic analysis. Bulk density of the product was measured to be 1190 ± 1 kg m^{-3} and particle size in the most common metric was D_{70}, specifying 70% of the particles in the dried product were retained on a 2 mm opening sieve. Moisture contents of the product on a dry basis and a wet basis were 18.4% and 15.6%, respectively. Mass balance of water was as follows (see Figure S2 also):

$$Mass\ of\ water\ removed(Y) = Mass\ of\ feed - Mass\ of\ water\ in\ product \tag{4}$$

$$Y = 68\ (\text{kg}) - 2\ (\text{kg}),\ \Rightarrow Y = 66\ (\text{kg})$$

Therefore, on average 66 kg of water was removed from the total 80 kg feed. That is 784 N loads on the unit per batch during the whole drying process. For the recycling process, energy was consumed in two forms, LPG for operation of the burner, 45.8 MJ per batch, and electric energy to run the mixing spindle moving at 80 rpm on a 2 HP, 220 V DC shunt motor, 3.6 MJ per batch. Total energy consumption was therefore 49.4 MJ per batch, simplifying to 0.9 kWh kg^{-1} and specific energy consumption was 0.2 kWh kg^{-1} of water removed. Figure 2 compares different drying techniques adopted for recycling of rural slaughterhouse waste in terms of energy consumption. The water removal rate or moisture extraction rate (MER) was ascertained as 18.9 kg h^{-1} and the specific moisture extraction rate (SMER) was determined to be 4.8 kg kWh^{-1}. These values suggest the proposed drying unit to be capable of providing better and efficient drying when compared with moisture extraction rates for other existing dryers used, such as the condensing tumble dryer very commonly used in household drying, having a MER 0.90 kg kWh^{-1} [39]. Similarly, Mustaffar et al. [40] discussed the moisture extraction rates of spray drying (0.5–1.0 kg kWh^{-1}) and a hybrid heat pipe screw dryer (2.04 kg kWh^{-1}). However, the MERs of other heavy dryers such as compression and heat pump types (10 kg kWh^{-1}) are higher than ours. The energy consumption of composting is 0.07 kWh kg^{-1}, which is the lowest among the available methods for recycling slaughterhouse wastes. However, composting cannot compete with alternate methods in terms of the time required for recycling [41]. Moreover, incineration necessitates >850 °C temperature to produce inorganic ash from organic waste. Rendering units are generally steam operated at 150–160 °C and 6 bar pressure [42]. The processing temperature is much higher compared to the temperature maintained in our novel drying unit (90–110 °C). Anaerobic digestion, on other hand, a multi-stage biological process, is generally carried out in mesophilic conditions (at 35 °C) for much longer durations (15–30 days) and/or thermophilic conditions (at 55 °C) for 12–14 days [43]. The high proteinaceous matter of blood makes it a problematic substrate for anaerobic digestion [23]. Moreover, implementation of anaerobic digestion in India has recurrently failed in the real field situation due to impractical suppositions on biowaste quality and quantity, miscalculation of the complicated biowaste supply chain, inappropriate anaerobic digestion designs and misjudgment of financial returns from biogas and digestate [44].

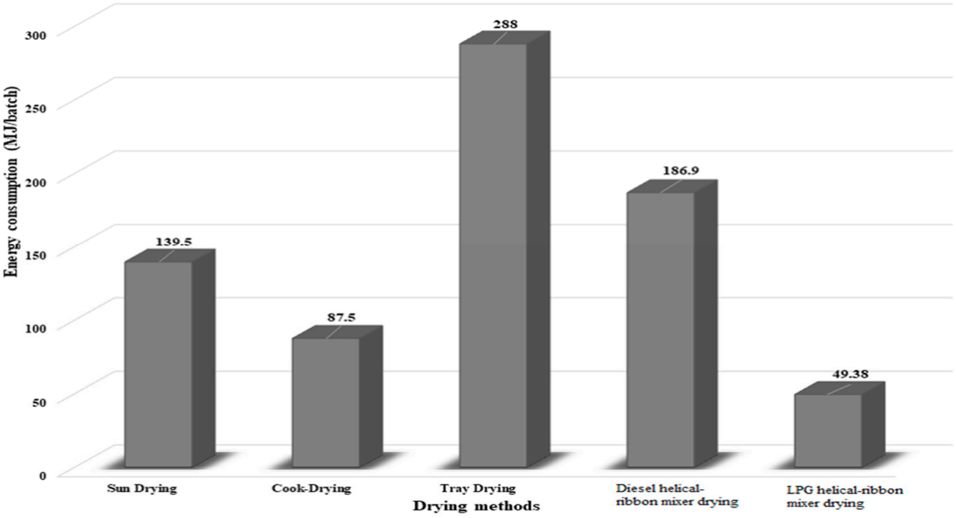

Figure 2. Drying techniques and their energy consumption adopted for rural slaughterhouse waste recycling in this study.

3.3. Experimental Drying Curves Obtained during the Drying Process

Observed data for the drying rate, drying time and moisture content on a wet basis are represented in Supplementary Table S1. Slope of the drying curve (Figure 3) (dx/dt) was constant till critical moisture x_c was attained; till this point the curve was linear. The nature of the drying rate curve can be visualized from the data plotted between time and drying rate shown in Figure 4. From initial point A of drying, the rate increased gradually till point B, where material to be dried was cold and slowly gained temperature to accelerate the drying rate. From points B to C, the drying rate remained constant as the unbound moisture evaporated. The water remained on the surface and water activity was one in this period maximum moisture removal occurred [45]. The C-E part of the curve represents the falling rate period: the drying rate in this period started decreasing as water activity dropped below one on the surface of the material. The falling rate period is divided in two parts: the first falling rate period (C-D), where wet surface of the material diminished to a few wet spots; and the second falling rate period (D-E), where the surface was completely dry and evaporation of internal moisture occurred. The equilibrium moisture content was attained at point E and drying rate was reduced to zero. The Krischer (time-independent) curve was plotted between drying rate and moisture content on a wet basis (Figure 5). It was derived from the plots shown in Figures 3 and 4, showing four phases of drying: adjustment period, constant rate period and falling rate periods I and II. The constant rate period continued till point C, which marked the end of the constant drying phase and the material entered the first falling rate period, which continued till point D and further till point E as the second falling rate period. The moisture removal curve was plotted between moisture removed (as percentage) and time (Figure 6). The drying rate became zero as equilibrium moisture content was achieved. Beyond that point drying had no further effect on water removal; moisture trapped in material is considered as internal moisture that is not possible to remove through physical treatments like drying [46]. All the above curves showed similar shapes and trends as analyzed for experimental drying kinetics by Kemp et al. [47].

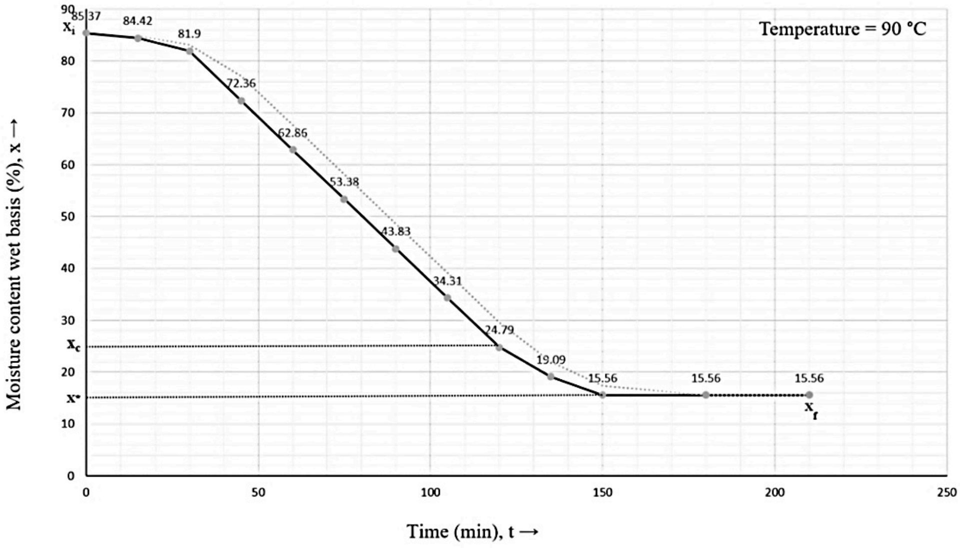

Figure 3. Drying curve and moisture content on a wet basis vs. time showing decrease in moisture content of the raw material during drying in the helical-ribbon mixer dryer. $x_{i,}$ x_c, x^* and x_f points on the curve represent initial, critical, equilibrium and final moisture contents, respectively.

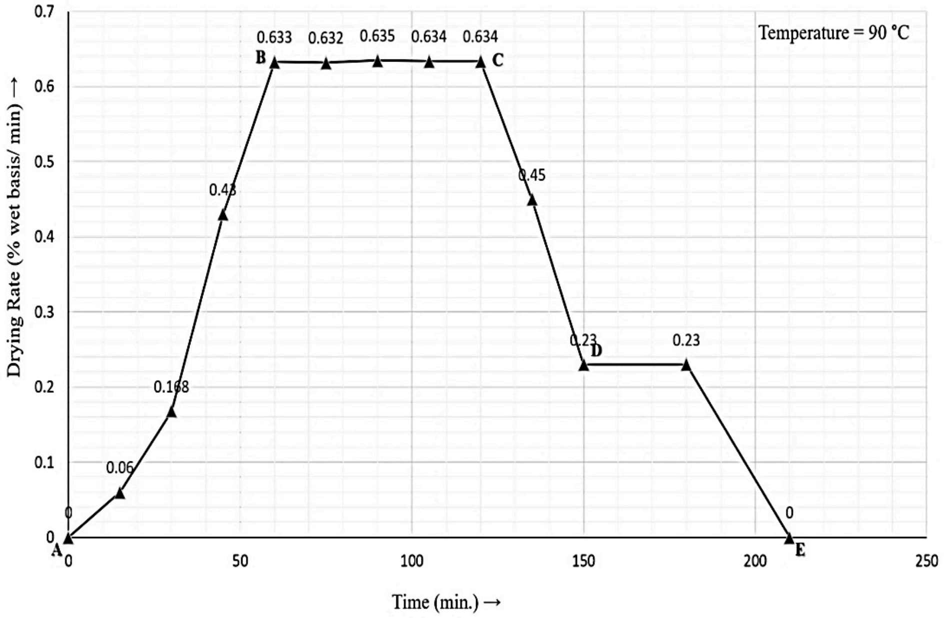

Figure 4. Drying rate curve—drying rate vs. drying time observed during drying of slaughterhouse waste in the helical-ribbon mixer dryer. A-B shows the initial adjustment period, B-C represents the constant drying rate period, C-D and D-E show the falling rate periods I and II, respectively.

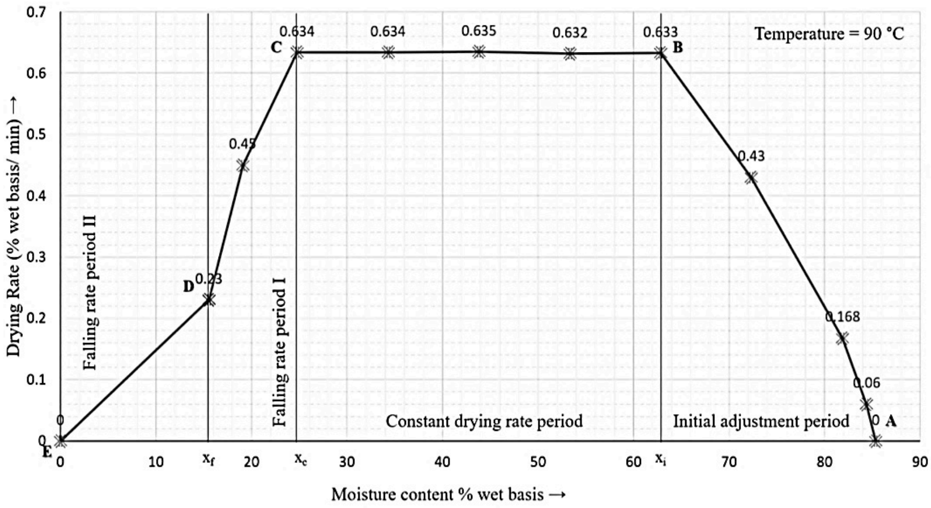

Figure 5. Time-independent or Krischer curve, drying rate vs. moisture content (% wet basis) showing constant rate period (B-C), first falling rate period (C-D) and second falling rate (D-E) during drying in the helical-ribbon mixer dryer.

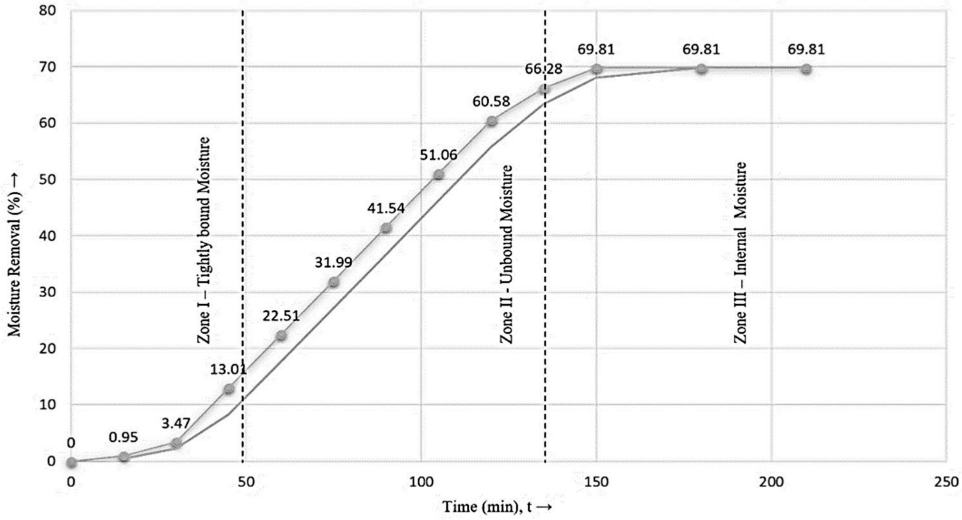

Figure 6. Curve showing the nature of water removal from feed trending over the three zones of moisture within the material.

Whereas García-Bernet et al. [48] represented a schematic of a drying curve that showed a plot between evaporation flux and mean moisture content for anaerobic digestion, no characteristic curves were reported. There are no reports on drying curves obtained for other slaughterhouse waste treatment processes such as rendering and pyrolysis. In contrast, the drying time in an air dryer is 8.2 h, a freeze dryer requires 41.23 h and a microwave dryer 0.25 h [49]. The fabricated helical-ribbon dryer requires lower energy consumption and less drying time. Removal of moisture from abattoir wastes not only reduces the waste-volume, adding value to the waste, but also inactivates biochemical reactions within the waste [50]. Existing industrial scale drying units such as flash drum dryers, spray dryers, bio drying and fried drying have complicated mechanisms and expensive attachments. The present methods for the disposal of rumen digesta are ensiling and drying by fluidized bed dryer, which entails high processing and operational costs [23]. Therefore, rural slaughterhouses, lacking in facilities, resources and infrastructure, would tend to choose cheaper, easier and profitable operations as described in this communication. According to Jiang et al. [49] the energy consumption for freeze drying (75.8 kWh kg^{-1}), air drying (49.2 kWh kg^{-1}) and microwave drying (4.38 kWh kg^{-1}) is much higher than that required for our process. Although these drying methods are applicable for blood waste recycling, they demand huge energy consumption, which is not suitable for poorly facilitated rural abattoirs of developing countries [51]. On the other hand, the energy consumption of the proposed dryer is 0.21 kWh kg^{-1}. Freeze drying takes up to 11 h to obtain the desired final moisture content of 12–15% on a wet basis. Another drying alternative, pulse-spouted microwave vacuum drying, has a drying time of 6 h [52]. Then again, such drying technologies are highly expensive and complicated to be introduced in abattoirs located in underprivileged rural areas and, therefore, such drawbacks necessitated development of an efficient drying technique that reduces the drying time, energy consumption and at the same time produces good quality dehydrated product [53]. Developing countries such as Ghana use drying beds for treatment of various organic wastes including animal carcasses. This method is time consuming and the drying time is up to 10–15 successive days [54].

A comparative study of different drying methods used previously for production of BBRDM and the currently described recycling method is presented briefly in Table 2. Results show lower energy consumption, decreased drying time and increased production per batch in the novel helical-spindle drying system. The drying curves obtained for sun drying, cook drying and tray drying indicating the final moisture content achieved after 13 h of the different processing methods are shown in Supplementary Figure S3. No characteristic drying curves were obtained as there is uneven distribution of heat and prolonged drying time. These processes have other limitations such as long drying time of up to 3–4 days in case of sun drying and 8–10 h when dried in a ten-tray modeled tray dryer. A tray dryer requires comparatively more labor for loading and unloading trays and materials being dried are always susceptible to undergo oxidation because the drying medium is heated air. In open sun drying there is always a chance of contamination of dust, dirt, insects, rodents and atmospheric pollution that can compromise the product quality [55]. Materials exposed to heat for a longer time have a lower nutrient quality as a dried product. Simultaneously, longer drying time leads to increased energy consumption, raising the capital cost [51,56].

Table 2. Comparative study of drying methods used for the production of BBRDM and their effectiveness in pathogen elimination.

Evaluating Parameters	**Method of Drying for BBRDM Production**				
	Sun Drying	**Cook Drying**	**Tray Dryer**	**Helical-Ribbon Dryer (Diesel)**	**Helical-Ribbon Dryer (LPG)**
Energy consumption (MJ/batch)	139.5	87.5	288	186.59	49.38
Amount of fuel consumption	-	5 kg Wood	80 kWh electricity	5 L +2 kWh electricity	1 kg +1 kWh electricity
Drying temperature (°C)	30–35	50–60	70- 80	65–70	90–110
Drying time (h)	72–96	5–6	9–10	4.5	3.5
Moisture content (%)	19–21	23–25	15–18	18.8	15.6
Production/batch (kg)	5–6	4–5	8–10	8–10	10–15
Nitrogen content (mg kg^{-1})	Not determined	49,440	5977	12,678	15,456
Pathogen inactivation	+	++	+++	+++	+++

BBRDM: Bovine-blood-rumen digesta mixture, +++: complete pathogen eradication, ++: incomplete pathogen inactivation, +: not effective.

3.4. End-User Readiness for Accepting the Recycling Process

For developing a sustainable bio-economy, the foremost step is to assess the consumer (local farmer) needs, their awareness about the recycled fertilizer (BBRDM) and affordability. Agriculture emerged as the prime occupation of the farmers followed by secondary occupation of slaughtering, “zari” embroidery and fishing. Sixty-nine percent of farmers cultivated their own land and 67% of farmers did farming themselves not depending on hired laborers; thus the decision of fertilizer choice rested on them. Seventy-two percent of farmers cultivated their land twice a year, 20% farmers cultivated thrice while 8% did it once every year. This cropping intensity indicated high demand for fertilizer. Forty-six percent of farmers mainly cultivated cereals and vegetables in rotation, 38% of farmers cultivated only vegetables while the rest cultivated only cereals. Forty-five percent of farmers grew two types of crops, 38% farmers three types while 17% of farmers cultivated a single type of crop in a year. Forty-nine percent of farmers used chemical fertilizers in agriculture, 32% of farmers used both chemical and organic fertilizers while 19% of farmers used only organic fertilizers for cultivation. Seventy percent of organic fertilizers used by the farmers were mainly of animal origin (48%) and the rest of plant origin (22%). The farmers also reported the use of pesticides during cultivation, of which 82% were of chemical and 18% were organic in nature. The total amount of investment was mainly focused on buying fertilizers. Eighty-seven percent of farmers wanted to consume organically grown food, as they were aware of the better nutritional quality of organically grown food. Among the respondents, 45% were willing to prepare BBRDM themselves and use it as a fertilizer while 55% of farmers were keen to purchase BBRDM and use it.

3.5. Supply Sector Readiness for Delivery of BBRDM

Here we estimate the overall cost of fabrication and installation of the novel helical-spindle dryer and yearly production of BBRDM. Total cost to be incurred by the abattoir owners includes those expenses that are one-time investment and are unlikely to occur again after initial setup of the production (non-recurring costs) as well as recurring costs (including labor costs) that would be contracted throughout each year. For our proposed recycling unit:

Non-recurring costs (INR)	
Equipment fabrication cost	250,000
Water connection	10,000
Sub-total	**260,000**
Annual recurring costs (INR)	
Operation and maintenance costs	50,000
Fuel and electricity charges	100,000
Local transport	20,000
Sub-total	**170,000**
Annual labor cost (INR)	
One skilled laborer @ 10,000 per month.	120,000
One manager @ 20,000 per month	240,000
Sub-total	**360,000**
Total cost (INR)	**790,000**

Assuming 5% of days in a year are non-productive, total production days = 347 days. Production per day is 60–70 kg. The calculation is made at the lower end taking 60 kg per day. The price of the recycled product is calculated considering 5% profit over production cost per year (Table 3).

Table 3. Calculation of product cost (INR).

Year	Non-Recurring Cost	Recurring Cost	Labor Cost	Total Cost (per Year)	Annual Production (in kg)	Price (INR. per kg)
Year 1	260,000	170,000	360,000	790,000	21,000	39.50
Year 2		170,000	360,000	530,000	21,000	26.50

3.6. Interest and Depreciation

The economic viability of the project was calculated with the assumption that 50% of the project cost will be financed through debt and the balance of 50% through grant/equity. Two alternate scenarios have been envisaged: (a) a loan with repayment period of 5 years, and (b) a loan with repayment period of 8 years where principal and interest moratorium of 1 year and interest rate of 8% per annum have been assumed. Since this project deals with an agricultural product, therefore it is eligible for a loan from the National Bank for Agriculture and Rural Development, India (NABARD). Hence, the interest rates charged by NABARD for loans of similar maturity have been used for the project cost calculations. Depreciation of fixed assets has been calculated at 10% per annum following a straight-line method. All recurring costs have been adjusted to an inflation rate of 7% per annum. Proposed scale of operation was for each abattoir, as these rural slaughterhouses are small in size and scattered all over the region under study. Six slaughterhouse owners of Magrahat II block, South 24 Parganas of West Bengal, India were surveyed regarding the investment cost and additional income that each slaughterhouse can earn on adoption of the recycling system. At the time of writing these abattoir owners earned a profit of INR 300,000 to 400,000 annually on their primary business of meat and byproducts such as bones and hide. Once the recycling unit is installed and fertilizer production was started, each slaughterhouse would be able to earn an additional income of INR 100,000 annually by investing INR 200,000 as capital expenditure. The slaughterhouse owners were willing to cover the investment costs through a bank loan.

3.7. Financial Viability

Since 50% of the project cost could be financed through debt, the most important concern is whether during the tenure of the debt the project could generate adequate cash in order to repay the loan and service interest thereon. The measured “debt service coverage ratio” (DSCR) has been deployed to test this criterion. The average DSCR calculated for a loan with a 5-year repayment period is 3.23 and the same for loan with 8-year repayment period is 4.63. Both the figures are found to be well above the required value of the DSCR (1.00). During both 5-year and 8-year repayment periods there is a positive cash balance after servicing debt, thereby signifying that the project is attractive to both the debt and equity investors.

In general, the quality of a fertilizer is determined by the available nitrogen in the particular type of fertilizer. Cost per unit of available nitrogen differs widely among fertilizers, feather meal being the least and fish meal the most expensive [57]. In the local market of district South 24 Parganas, where the study was carried out, cow dung was the cheapest (INR 30 per kg) and horn dusts found to be most expensive (INR 150 per kg). The selling price for mustard cake, vermicompost, neem cake and bone dust varied between INR 60 and 80 per kg. Inorganic fertilizers such as urea, diammonium phosphate (DAP), N/P/K = 10:26:26 etc., are usually sold at INR 30–35 per kg, whereas BBRDM (product under study) was costed as INR 26.00 per kg, which was reasonably lower than the competitive products. High-rate bio-methanation and rendering have been suggested for large slaughterhouses by the Central Pollution Control Board, Government of India, while composting has been recommended for small-scale slaughterhouses. To circumvent the inherent disadvantages of composting, the production of BBRDM is being proposed. The operation of the BBRDM production units is financially viable and economically attractive to the slaughterhouse owners who are reluctant to relocate in centralized areas and do not want to invest in the high cost-intensive conventional wastewater treatment plants suggested by the regulators. Furthermore, the BBRDM production unit can generate employment opportunities as the skill required for running the BBRDM plant is low. As perceived by the economic survey, the product (BBRDM) would be acceptable to the local farmers, thus creating a ready market for this organic fertilizer.

Results of this investigation corroborated the observations of Donner et al. [30]. The public perception of “green products and processes” favor business development, particularly because they may be locally produced by exploiting nature-based functionalities. The local dimension of valorizing agricultural waste through the participation of local stakeholders is crucial for all individual businesses and more easily attained in cases where local employment and engagement is created by the initiative [20,30]. Authors further opined that the transformation of linear chains to a circular economy in the agricultural sector allowed individual business models to evolve towards more dynamic and integrated business models, with a high degree of interaction of all actors (university researchers, local communities involving slaughterhouse owners and farmers in this case study) in a local context. Hence, their strategies are interlinked and can be mutually influenced. This implies that the business model of an individual company (here slaughterhouses) may be impacted. Additionally, more integrated business models are expected to emerge leading to successful co-creation of value in a territorial circular economy.

4. Conclusions and Policy Implications

The performance of the proposed dryer was evaluated on site. (i) Experimental curves followed the accepted trend of drying. Drying time and energy consumption were reasonably lower compared to the previous methods of BBRDM preparation. (ii) As the conductive helical-spindle dryer presented in our work is portable, lacks in complicated attachments, and no sophisticated and expensive technologies are used, this dryer can be easily installed in scattered units of rural slaughterhouses. (iii) Considering the domestic and global demands for organic farming-based produce, small abattoir owners can emerge as multi-product producers to enhance net private earning. At the same time farmers can source the fertilizer locally for organic farming. The two activities can emerge as complementary to each other and become a model for circular economy with a full waste recycling system within the local economic structure. (iv) Economic analysis demonstrated that the project is attractive to both the debt and equity investors. This effort has potential to protect the livelihood of approximately 30,000 small-scale informal slaughterhouses in India as they are facing institutional and legal pressure to stop current unhygienic waste disposal by closing their businesses for environmental protection. The presented technology development will be beneficial to such informal abattoirs to attain a cleaner environment and enhance secondary income through circular economy. Development of a business model was the secondary objective of this study. Social acceptance of this new technology depends on multiple indicators: credit worthiness, financial mechanism, policy and regulations, or it can be market driven. This study theoretically shows financial viability of the product from the new technology which is the first step towards social transition, the maturity of which depends on the presence or absence of enabling conditions.

Small slaughterhouse operations create a large number of livelihood opportunities. At the same time, small-scale farmers (who may or not be slaughterhouse owners) are looking for options to enter the expanding market for high-valued organic farm-based produce. We have provided a scope for socio-technical innovation in rural and peri-urban areas. We intend to address the local societal demand for an economically viable technological solution and to deliver economic and environmental solutions. There is growing demand for organic farming-based produce which is also seen as a potential remedy for nutrition demand with lesser environmental impacts compared to conventional chemical fertilizer-based agriculture [27]. Initiatives may be undertaken to engage with local abattoir owners and agricultural farmers to develop and socially embed this sustainable technology for waste processing and providing farmers with an affordable locally available organic fertilizer. Donner et al. [30] observed that the local context directly impacted business models to become more dynamic and integrated with the involvement of other territorial players. The new, more dynamic and integrated business models allowed valorizing agricultural waste, disposing of material fluxes locally, hence fulfilling the requirements of circular economy which were distinctly demonstrated through this investigation. Besides, the local context also supported public–private partnerships, involving general citizens as consumers of local products as participants in valorizing agricultural waste.

Organic fertilizer production from waste treatment, for example application of the digestate derived from anaerobic digestion as an organic fertilizer, has gained attention in India but with limited success so far. The potential of digestate application is not fully utilized as farmers are not aware of the use the digestate. Absence of relevant end-user training programs is the reason for the failure. However, recent environmental policies in waste, energy and agricultural sectors in India have set important foundations for broader diffusion in the near future [44]. Various components that need to be developed for social embedding of new technology targeted at a circular economy model include continuous technological improvement till it reaches maturity, price of the organic fertilizer, policy intervention and institutional reorganization that can create enabling condition for further scale-up. This appropriate, affordable and efficient methodology for recycling of waste generated by small abattoirs can be a model in many developing countries with similar dispersed small-scale traditional slaughtering practices with no hygienic waste disposal system.

5. Patent

Indian patent number 370569 on the proposed dryer has been granted.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13169455/s1. Figure S1: Helical-ribbon mixer dryer constructed based on Figure 1 and currently installed in one of the rural abattoirs of Magrahat, South 24 Parganas, West Bengal (India). Figure S2: Mass balance of moisture removal from slaughterhouse waste in the developed helical-ribbon mixer dryer, where 1 and 2 represents input and output sides of the drying system, respectively. Figure S3: Comparative study of recycling alternatives applied previously to rural slaughterhouse wastes, namely tray drying, sun drying and cook drying based on achieved final moisture after 13 h of processing. Table S1: Changes in drying rate and product moisture with the progression of time observed during the operation in LPG-fueled helical-ribbon mixer dryer. Video S1: Helical-ribbon mixer dryer in operation.

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