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Research paper

Science based approach for translating water hyacinth menace into wealth for agricultural sustainability: Empirical evidence from rural India

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ABSTRACT

Despite numerous reports on valorization of water hyacinth biomass, its wide-scale adoption has not been realized. In Puri district there are about 2100 water hyacinth infested rural ponds and harvested water hyacinth biomass remain unutilized on the banks of these ponds. The work presented is an attempt to evaluate techno-economic viability of aerobic composting of water hyacinth biomass as an alternative livelihood option. A rural enterprise undertaking aerobic composting of water hyacinth biomass was established in the Nimapada block of the Puri district of Odisha, involving rural women SHG members. The nutrient rich harvested biomass was used for aerobic (windrow method) composting along with suitable quantities of paddy straw and cow dung by women self-help group members. A commercially available enriched microbial consortia was used at the rate of 1 kg per ton of mixed biomass to facilitate efficient aerobic composting. Our study found that freshly harvested water hyacinth biomass, paddy straw and fresh cow dung mixed in the ratio of 7:2:1 is optimal for aerobic composting. The C/N ratio and organic carbon content for the optimum biomass mixture was 16.94 and 14.1 mg/kg respectively. The cost of production of this compost was found to be Rs.8 per kg considering all cost components such as raw material cost, local transport cost, labour cost, fuel cost (shredding of fresh biomass and sieving of final compost), weighing and packaging cost etc. A total of 600 tons of compost was prepared involving trained women SHGs in the Puri district.

1. Introduction

Water hyacinth or *Pontederia crassipes* (formerly *Eichhornia crassipes*) is an aquatic weed native to Amazonia [1]. This free-floating vascular plant is one of the worst weeds known to humankind [2]. Anthropogenic water pollution, agricultural run-off, deforestation, and inadequate wastewater treatment are the main causes of widespread water hyacinth infestation [3]. The ability to outcompete native vegetation and phytoplankton for sunlight as well as nutrient and absence of natural predators are the reasons behind its invasiveness. Severe water hyacinth infestation has been a major contemporary environmental challenge in more than fifty countries. Tropical and sub-tropical regions, with hot-humid climate and abundant sunshine, particularly suffer from water hyacinth infestation [4]. As a result of climate change, average surface water temperatures are rising across the world and hence water hyacinth infestation is likely to spread to higher latitudes in the coming decades [5]. The weed forms dense and interlocked, floating mats, on the surface of the infested water bodies [6]. Water hyacinth reproduces both sexually and asexually and has a fast growth rate in eutrophicated water bodies. Each water hyacinth plant produces about 4500 microscopic seeds which get deposited in the benthic sludge. These seeds remain viable for decades in tropical and subtropical conditions. Dry conditions promote seed germination [7]. These seeds become unviable when exposed to sub-zero temperatures or temperatures above 57 °C [8]. This is one of the reasons why water hyacinth infestation is more common in the frost-free regions of the world [9]. Nutrient concentrations as well as ambient temperature affect the growth rate of water hyacinth which is the reason behind its emergence, disappearance and reemergence in different sections of a surface water body during different seasons of the year [3]. This aquatic weed can survive in salinity ranges between freshwater (<0.5 ppt) and oligosaline conditions i.e. 0.5 – 5.0 ppt (parts per thousand) while experience necrosis in mesosaline (5 ppt-18 ppt) and polysaline (above 18 ppt) conditions. As increased salinity adversely affects water hyacinth growth, in the tidal

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creeks and estuaries, it grows rapidly during low-saline period and die-off during the high-saline conditions. The periodic sinking of large water hyacinth mats leads to siltation of these water bodies. Water hyacinth infestation affects the water quality by reducing the dissolved oxygen concentration, limiting sun-light penetration and rapid nutrient uptake (particularly nitrate and phosphate). Unlike phytoplankton and submerged vegetation, water hyacinth does not release oxygen into the water column [10]. Other effects include increased water turbidity, sedimentation rate and water loss due to evapotranspiration [11]. Due to the combined effect of these changes water hyacinth infestation alters the original community composition and food-web structure in the infested water body.

In India, water hyacinth infestation is common in the eutrophicated surface water bodies near human settlements. Puri is a coastal district in the Indian state of Odisha with a tropical wet and dry or savanna climate (classification: Aw). The district is at the sea level with an annual mean temperature is 29.04°C. Early residents of Puri used to dig up a portion of their lands and utilize the excavated soil for making earthen houses. This practice has led to the ubiquitous presence of ponds across the district. As per some estimate >2100 ponds are in Puri, mostly below 0.5 acre in size. Few of these village ponds are under community ownership while a vast majority of them are under private ownership. Population growth over the last several decades has increased the wastewater inflow from nearby human settlements to these ponds turning them eutrophic. These eutrophicated ponds provide ideal conditions for water hyacinth growth and propagation (Fig 1). It is extremely difficult to eradicate water hyacinth from an infested water body in an economical and environmentally benign manner. Hence, only occasional harvesting of water hyacinth mats from the infested ponds are conducted by the local volunteers in these villages. Frequent harvesting of water hyacinth and disturbance of the mat significantly reduces the degree of infestation, unlocking the potential of these ponds for inland pisciculture and aquaculture. Frequent harvesting though becomes difficult and financially unviable.

Utilization of the harvested water hyacinth biomass and revenue generation through a rural enterprise thus provides a scalable and techno-economically feasible solution to water hyacinth infestation for these villages. Over the last few decades researchers have highlighted the potential use of water hyacinth biomass for biogas production, bioethanol production, compost preparation, production of antimicrobial compounds etc. [1]. After consultation with local stakeholders, the aerobic composting of water hyacinth biomass was found to be the most feasible revenue generating option for the villages of Puri considering existing demand for compost among the local farmers. High nitrogen, phosphate and potassium content as well as relatively low lignin content in the water hyacinth biomass makes it amenable to aerobic composting [8]. Researchers [4] in countries such as Sri Lanka [12], Uganda [13], Nepal [14] have reported potential use of water hyacinth biomass for composting.

Despite the known potential of water hyacinth biomass as a nutrient rich biomass amenable to aerobic composting, wide scale utilization of this biomass involving local stakeholders is rare. This highlights the gap in our present research, understanding particularly about the profitability of aerobic composting of water hyacinth biomass as a rural enterprise. The work presented covers all aspects of this ‘waste to wealth’ interventions such as harvesting, sourcing of paddy straw and cow dung, shredding of biomass, heap preparation and maintenance, sieving and packaging etc. to avoid hidden cost components in the business model presented which often make published ‘business models’ unviable in field conditions. The study attempted to provide accurate estimation of the cost of production in actual field conditions while highlighting that due to the high moisture content of the harvested biomass, the activity should be conducted in a piece of land near an infested water body to ensure economic feasibility as a rural enterprise. A standardized protocol was developed for large-scale utilization of water hyacinth biomass for aerobic composting. The study found that a ratio of 7:2:1 for shredded water hyacinth, paddy straw and cow dung (all in terms of fresh weight) is optimal for aerobic composting. The production cost (Rs. 8 per kg) was calculated considering all cost components to provide clear ideas about profitability (Rs.2 per kg). As the entire process of harvesting water hyacinth biomass to sale compost produced takes about 80–100 days, the pay-back period is short for this business model. The focus of the work was to demonstrate how through appropriate capacity building and technical handholding women self-help group (SHG) members can create alternate livelihood opportunities through aerobic composting. The work highlighted that local procurement of paddy straw and cow dung leads to wider distribution of economic benefits and greater community ownership of the intervention amongst the villagers. The field data generated from this work would enable wider adoption of such scalable scientific solutions. A total of six

Fig. 1. Water hyacinth infestation in Puri, Odisha (village: Mulabasanta, block: Kanas).

hundred tons of compost was prepared over a period of two years and consistent compliance with the FCO (Fertilizer Control Order) norms highlighted the reliability as well as scalability of the intervention.

2. Materials and methods

2.1. Feasibility survey and stakeholder consultation

After consultation meetings with local stakeholders and assessment of availability of water hyacinth biomass, cow dung and paddy straw by field survey across the district, the Arjunpur village of the Nimapada block of Puri was identified for this activity. Land availability and interest among local SHGs were also key factors considered for site selection. A suitable patch of land, which was not prone to water logging, adjacent to an infested rural community pond, (latitude: 20.08125° N; longitude: 86.02606° E) was identified for the activity (Fig 2). Multiple formal and informal awareness generation activities were conducted involving local concerned officials, gram panchayat members and women SHG members to facilitate knowledge sharing. The importance of such exercises in dispelling misconceptions and foster mutual trust cannot be over emphasized. Land clearing and levelling was done involving local villagers at the onset of the activity. Harvesting of the water hyacinth biomass was conducted manually and using bamboo poles, ropes and fishing nets. Main cost of water hyacinth biomass procurement for aerobic composting was this manual harvesting cost in terms of wages (Rs.450 per day per labour). Site being adjacent to the pond, no transportation cost was associated.

2.2. Evaluating optimized biomass ratio for aerobic composting

Size-reduction of plant biomass reduces the time-period required for aerobic composting by increasing the surface area and by exposing softer inner tissues which are often more amenable for microbial biodegradation. Both water hyacinth and paddy straw were shredded to <5 cm size pieces using a chaffcutter (Make: Bhide, Model: CS - 50/T) before heap preparation. Due to the wetness of the harvested water hyacinth biomass, it was kept as a heap in ambient condition overnight, after harvesting, to facilitate drainage of excess water before shredding. Previous researchers highlighted that initial C/N ratio of raw materials affect nitrogen mineralization and a C/N ratio of about 25:1 ensures adequate availability of nitrogen for microorganisms to facilitate biodegradation. Low C/N ratio (<20) loses nitrogen faster than ammonia whereas high C/N (greater than 35) ratio slows down the decomposition rate and hinders humification (Hao and Benke, 2008). Moreover, the C/N ratio influences the duration of the thermophilic phase and peak temperatures both critical to ensure effective deactivation of pathogens. Water hyacinth biomass tends to have a C/N ratio close to 20 and a high moisture content of about 85 %. Hence, mixing water hyacinth biomass with a carbon rich biomass such as paddy straw makes the mixture ideal for aerobic composting. However, the optimal ratio for these two readily available biomasses for aerobic composting, has remained undocumented for field-conditions of India. Aerobic composting uses microbial consortia to facilitate faster biodegradation. Cow-dung provides an ideal medium for this consortia to rapidly multiply and spread across the biomass heap uniformly. A cow-dung slurry mixed with appropriate quantities of microbial culture, hence was used to drench the biomass heap prepared with shredded water hyacinth and paddy straw, to facilitate efficient and uniform aerobic composting. Microorganisms present in microbial culture, grow rapidly in the cow dung slurry and reduce the waste to microorganisms which in turn facilitate faster biodegradation. Different ratios of shredded water hyacinth and paddy straw were mixed to prepare 100 kg heaps of mixed biomass (Table 1). Cow dung slurries were prepared with varied quantities of cow dung and 100 g of microbial culture (Make: Excel, Product Name: Madhyam) for each of the biomass heaps to facilitate aerobic composting. Heap turnover and watering was conducted manually at an interval of 12 days for the 65-day period. Temperatures of each heap were noted daily using battery operated digital multi-stem thermometer (Make: MEXTECH, Model:ST9283B) connected to each heap.

2.3. Bulk heap preparation for aerobic composting

The fresh weight of the total water hyacinth biomass harvested (Fig 3) from the 2.76-acre pond (~72,000 kg) was mixed with 20,570 kg paddy straw procured locally and 10,285 kg fresh cow-dung. Water samples were collected from the pond in Arjunpur village and analyzed for physical and chemical characteristics [15] using APHA (American Public Health Association) Standard Methods listed in Table-S1. Shredded paddy straw and water hyacinth biomass were mixed with cow-dung to prepare multiple rectangular shape compost heaps as per the optimal biomass ratio mentioned in the section above. For every 1 ton of mixed biomass, 1 kg microbial culture was used by mixing it with cow-dung as a slurry. Biomass quantities were weighed using an electronic platform weighing balance with digital display (Make: Smart, Model: LAE66 PLAX, T-10–100; Capacity: 100 kg; accuracy: 10 g) and appropriate quantities of each biomass were mixed to make horizontal

Fig. 2. Site-identified in Arjunpur is marked in yellow colour lines (20.08144° N,86.02565° E).

Table 1
Constituent details of each experimental heaps and material cost.

	Constituents (fresh weight in kg)	Number of replicates	Cost of raw material (Rs)	Composting duration (days)	Instruments used
Heap 1	Water hyacinth: 60 Cow dung: 20 Paddy straw: 20 Microbial culture: 0.1	3	136	65	1. Platform scale (PLAX-TP 500–150K10)
Heap 2	Water hyacinth: 80 Cow dung: 20 Paddy straw: 0 Microbial culture: 0.1	3	132	65	
Heap 3	Water hyacinth: 70 Cow dung: 20 Paddy straw: 10 Microbial culture: 0.1	3	134	65	
Heap 4	Water hyacinth: 50 Cow dung: 50 Paddy straw: 0 Microbial culture: 0.1	3	139	65	
Heap 5	Water hyacinth: 70 Cow dung: 10 Paddy straw: 20 Microbial culture: 0.1	3	134	65	

stratified layers one upon the other (Fig 4). Shredded water hyacinth biomass was the bottom layer during the heap preparation upon which shredded paddy straw layer was put. The height of this layer was about 30 cm. Manual mixing of both the biomass was carried out followed by drenching of this heap with the cow dung and microbial culture slurry. Following the same process, four more 30 cm layers of biomass were built on top of this first layer yielding a final heap height of 1.5 m. Subsequently, after heap preparation, manual heap turnover and watering were carried out at an interval of 12 days. Heap temperatures were monitored using digital multi-stem thermometers (Make: MEX-TECH, Model:ST9283B) daily for all the heaps. Moisture content of different biomass and compost was measured with a digital moisture meter for all the heaps daily during the 65 days composting period (Make: Vunexo, Model: VU-SM-809). Final compost prepared were sieved using a 4 mm electrically operated sieving machine (Make: ALTECH Construction Equipment Limited, 1 HP electrical motor, length: 2.4 m; width: 0.6 m) and packed in synthetic gunny bags (Fig 5). Combined cost of the shredding (Rs.110,000), sieving (Rs.34,000) and weighing machine (Rs.5000) supplied to the SHG were Rs.153,000.

2.4. Analysis of biomass samples

Three samples of water hyacinth biomass and paddy straw were calculated while making each compost heap. These samples were analyzed at ICRISAT Patancheru. Plant samples were dried to a constant weight in the oven at 65+5 °C followed by grinding for the purpose of analysis. The samples were analyzed for N, P, K, sulphur (S), boron (B), calcium (Ca), magnesium (Mg), total iron (Fe), zinc (Zn), arsenic (As), chromium (Cr) and lead (Pb) in the Charles Renard Analytical Laboratory (CRAL) at ICRISAT, Patancheru. Total N, P and K in plant materials were determined by digesting samples with sulphuric acid-selenium. Nitrogen and P in the digests were analyzed using an auto-analyzer (Skalar SAN System, AA Breda, Netherlands), and K in the digests was analyzed using an atomic absorption spectrophotometer (Savant AA, GBC Scientific Equipment, Braeside, VIC, Australia). Zinc in plant samples was determined by digesting them with tri-acid mixture, and Zn in digests was analyzed using atomic absorption spectrophotometer. Total S, B as well as metal concentrations in plant samples were determined by inductively coupled plasma emission spectrophotometer (Prodigy High Dispersion ICP-AES, Teledyne Leeman Labs, Hudson, New Hampshire, USA) in the digests prepared by digesting the samples with nitric acid [15]. Biochemical analysis of water hyacinth biomass and paddy straw biomass were carried out for estimation of cellulose, hemicellulose and lignin content. Analysis of the fractions was carried out using the Van Soest Method of Cell Wall Determination. In this method soluble cell contents such as starches, proteins, sugars, pectin's, fats, vitamins, minerals, etc. are separated from the fiber fraction of the biomass. The fiber fraction of a sample is divided into two components that are neutral detergent fiber and acid detergent fiber (Van Soest 1994). Neutral Detergent Fiber (NDF) estimates the total fiber content of a sample (cellulose, hemicellulose, lignin). It is the insoluble part of sample in detergent under neutral conditions (Bruno et al., 1998). Acid detergent fiber (ADF) is the insoluble part of a detergent in acid conditions. It measures cellulose and lignin contents of a plant sample. It is the insoluble part of a detergent in acid conditions. ADF is also partially digestible. The difference between NDF and ADF gives the estimate of hemicellulose. The ADF is used as a preparatory method for lignin determination and lignin percentage was obtained after subtracting permanganate acid residue.

Fig. 3. Manual harvesting of water hyacinth mat.

Fig. 4. Bulk aerobic composting: A) Procurement; B) Shredding of water hyacinth; C) Shredding of paddy straw; D) layer of shredded water hyacinth; E) layer of shredded paddy straw; F) layer of fresh cow-dung; G) watering of heap; H) bulk heaps of compost; I) sun drying of compost.

Fig. 5. Sieving of sun-dried aerobic compost.

2.5. Analysis of compost samples

Three compost samples were collected from each heap at the end of the composting cycle and were analyzed to check for consistency. Collected compost samples were air dried, ground, and passed through a 2-mm sieve. Samples were ground to pass through a 0.25 mm sieve for compost organic carbon analysis following the Walkley-Black method [16]. For estimation of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in compost, 0.5 g of samples was digested using 3.5 ml sulfuric acid–selenium mixture [17]. N and P in the digests were estimated with the help of auto-analyzer, and K, Ca and Mg with help of atomic absorption spectrophotometer (AAS). For micronutrients, zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn), 0.2 g compost samples were digested with 2 ml tri-acid and contents in the digests were estimated using AAS [18]. S and B in samples were estimated through digesting 0.2 g samples with 2 ml nitric acid plus 0.5 ml hydrogen peroxide and determining the contents in the digest through Inductive Coupled Plasma Atomic Emission Spectrophotometer (Mills and Jones Jr 1996). The pH was measured in 1:2 water suspension (20 g sample and 40 ml water) using glass electrode and total carbon by Skalar TN/TC analyzer through using 1 g sample (Primacs SNC100 series).

2.6. Carbon credit calculation

In most cases, after harvesting the water hyacinth biomass remains dumped on the banks of the canal or lakes from which it was harvested. The activity is generally taken up in dry summer months and as the biomass dries up, the locals resort to open burning. The FPO undertaking the intervention would be the beneficiary of such carbon credits if monetized. Utilizing the biomass for aerobic composting essentially fosters a more environmentally benign waste management approach and reduces the carbon footprint of these rural communities. The overall system boundary of the valorization process of water hyacinth biomass through aerobic composting is highlighted in Fig 6 [19].

The formula for carbon credit and carbon footprint calculation is given below where WH represents dried water hyacinth biomass and PS represents dried paddy straw biomass. Carbon content of the overall biomass can be calculated from the percentage of carbon (% C) present in the dry biomass (equation 1) whereas percentage of nitrogen (% N) present in the water hyacinth biomass can provide carbon credit in terms of Urea (percentage of N 46.8) substitution considering 1 kg Urea is equivalent to 0.2 kg carbon. Processes involving fuel or electricity usage are considered as carbon footprint, in total three such processes are involved in aerobic composting viz. shredding, transport and sieving. The carbon footprint of each of these operations can be individually computed considering the hours of operation or fuel consumption etc. For example, shredding was carried out using a tractor operated shredder which was having a capacity of 1500 kg per hour and diesel consumption of 8 L/h. Similarly, local transport (<2 km) of biomass was carried out using a tractor with a capacity of 1500 kg per trip and average fuel consumption of 2 L per trip. Considering 1 L diesel is equivalent to 0.73 kg C, carbon footprint for shredding (CSh) and transport (CT) were calculated (equation 4 and equation 5). The sieving machine was driven by a 1 HP electrical motor with a capacity of 125 kg per hour. Hours of operation for the total compost (TC) quantity hence can be easily computed and C credit can be estimated considering carbon footprint of 1 HP electrical motor is 0.2234 kg C/hour. Subtracting total carbon footprint (TCD) from the total carbon credit (TCC), net carbon credit can be obtained as kg of C. As 1 kg of C is equivalent to

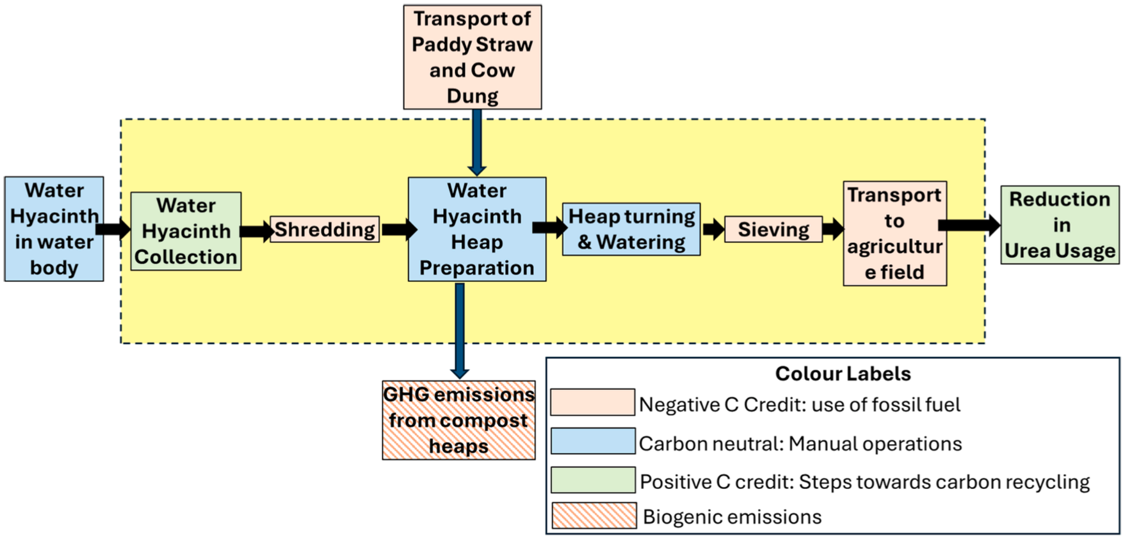

Fig. 6. System boundary of the composting process of the water hyacinth biomass.

3.67 kg of CO_2, net carbon credit as kg of CO_2 can be estimated.

$$\text{Carbon Credit for carbon content (CCC)} = (WH \times \%\, C) + (PS \times \%\, C) \quad (1)$$

$$\text{Carbon Credit for nitrogen content (CNC)} = [(WH \times \%\, N)/(0.468) \times 0.2] \quad (2)$$

$$Total carbon credit (TCC) = CCC + CNC \quad (3)$$

$$\text{C Footprint Shredding (CSh)} = [(WH + PS)/(1500) \times 8] \quad (4)$$

$$\text{C Footprint Transport (CT)} = [(WH + PS)/(1500) \times 2 \times 0.73] \quad (5)$$

$$\text{C Footprint Sieving (CSi)}: (TC/125) \times 0.2234 \quad (6)$$

$$\text{Total carbon footprint (TCF)} = (CSh + CT + CSi) \quad (7)$$

$$Net\ carbon\ credit\ as\ kg\ of\ CO_2 = 3.67 \times (TCC - TCF) \quad (8)$$

3. Results and discussion

3.1. Aerobic composting of water hyacinth biomass

Windrow or heap method is a proven method of composting around the globe [20]. Main advantage of this method is its capability to handle large quantities of biomass without necessitating any physical infrastructure like vermicomposting. Large-scale windrow composting facilities are present around the globe as a well-established method of sustainable soil waste management for amenable biomass such as agro-waste or leaf litter etc. Accurate estimation of the cost of production is very important to undertake aerobic composting of water hyacinth biomass as a rural enterprise. The fresh weight of one square meter of water hyacinth mat was about 13.49 kg while its dry weight was 2.02 kg indicating a moisture content of about 85 %. The average C/N ratio of dried water hyacinth biomass was 32.14 which is not ideal for aerobic composting as highlighted in Section 2.2. Moreover, the moisture content of the water hyacinth biomass high, addition of paddy straw, a carbon rich and much drier (moisture content: 15.8 %) biomass makes the mixture of both biomass suitable for aerobic composting. Because of the higher nitrogen concentration of water hyacinth biomass, mixing with other biomasses such as leaf litter, straw, saw dust etc. have been suggested as bulking agents by researchers [21]. Use of amendments such as cattle manure, poultry litter, rock phosphate, wood ash etc. have been reported to achieve optimum C/N ratio of the final compost. The high nitrogen (3.2 %), phosphorous (1.9 %) and potassium (1.35 %) content of the compost produced from water hyacinth biomass have been highlighted by previous researchers indicating the valorisation potential of this aquatic weed (Su et al. 2018). Field-scale studies on water hyacinth composting as a business model though are less reported in the literature. The work presented here provides details of methods and strategies adopted to make bulk production of water hyacinth biomass as a profitable rural enterprise. For example, harvesting water hyacinth mats even from a small rural pond yields several tons of biomass with very high moisture content. The 'pond' to 'production unit' cost of water hyacinth biomass has not been reported in published scientific literature. Long-distance transportation of this biomass in bulk quantity for value addition is simply economically unviable. In this study we have highlighted how undertaking aerobic composting of the harvested water hyacinth biomass in a piece of land adjacent to the infested water body can be a useful strategy which can circumvent this critical bottleneck. Adopting decentralized approach involving women SHG groups provided alternative livelihood opportunities for these resource poor villagers close to their home. It was found pre-planning and scheduling of different activities such as harvesting, weighing, heap preparation, watering, sieving, packaging can be undertaken by the SHG members all by themselves in an independent manner. Hence, unlike most other known usage of water hyacinth biomass such as in making handicrafts, decorative items or hand-made paper [22] aerobic composting can utilize bulk quantities of water hyacinth biomass near the source of the biomass incurring minimal capital investment or transportation costs involving local stakeholders. Thus, we found the intervention techno-economically feasible with higher long-term sustainability. The prevailing labour cost was Rs.450 (~$5) per person per day (for 8-h shift) and the total cost of harvesting for a 2.76-acre (~ 1.1 ha) pond was Rs.92,000. A total of 72,000 kg (fresh weight) was harvested and hence the cost of water hyacinth biomass was Rs.1.27 per kg of fresh weight. It is worth mentioning here that the pond was not completely covered with water hyacinth as shown in Fig 2 and coverage of the water surface was about 50 %.

3.2. Comparison of aerobic composts prepared for different combinations of biomass

Cellulose, hemicellulose, and lignin are the three main natural polymers present in plant biomass [23]. Compared to cellulose, a linear biopolymer and hemicellulose, which has a non-crystalline structure due to chain branching; the cross-linked polymer lignin, responsible for plants rigidity, is less amenable to aerobic composting. Proximate analysis of water hyacinth biomass highlighted a cellulose, hemicellulose and lignin contents of 24.45 %, 33.88 % and 9.22 % respectively whereas for paddy straw samples collected from our project village, cellulose, hemicellulose and lignin contents of 35.63 %, 17.57 % and 14.46 % respectively. The analysis reveals that both water hyacinth and paddy straw biomass with low lignin content are amenable to aerobic composting. Mixing of paddy-straw which has a high C/N ratio with nitrogen rich biomass such as dairy waste for aerobic composting has been previously reported [24]. In the work presented here, biomass mixtures prepared with different quantities of paddy straw, water hyacinth and cow dung (Table 1) were used for aerobic composting to evaluate the optimal ratio of these biomasses in-terms of final compost quality, cost of production over a period of 65 days. In total five biomass mixtures were evaluated, and three heaps were prepared for each of the five combinations making total number of heaps fifteen. Daily monitoring of heap temperatures was carried out and average heap temperatures observed for each of the five heap types is given in Fig 6 with standard deviation. Heap turning was carried out along with watering in 12 days interval to facilitate heat dissipation and to ensure moisture availability in the heaps critical for microbial biodegradation. In total heap turning and watering operations were carried out five times i.e. on 12th day, 24th day, 36th day, 48th day and 60th day during the 65-day composting period. A temporary drop, in the heap temperatures, was observed after watering. Pond water analysis (Table S1) highlighted the absence of any heavy metal and hence it was used to water the compost heaps. The average water quality data presented in Table S2 is indicative of an eutrophicated water body with inorganic nitrogen content of 4 mg/L. This pond located at the end of the village near the cremation ground is not used for washing clothes or utensils. Occasional bathing by the villagers post cremation was the main source of the rather low phosphate concentration of 0.027 mg/L observed. The occasional storm-water inflow and agricultural run-off were the only sources of pollution for this pond. This explains the rather low chemical oxygen demand (COD) of 25 mg/L (Baird and Bridgewater, 2017). It was observed during the experiment that the presence of paddy straw makes the heap more compact and facilitated a more distinct thermophilic phase. The final aerobic compost obtained from Heap 1, Heap 2, Heap 3, Heap 4 and Heap 5 each with an initial biomass weight of 100 kg were 34.5 kg, 18.2 kg, 26.3 kg, 19.2 kg and 34.2 kg respectively showing wide variation in yield. The moisture contents of the final compost for five heaps were within the range of 17.2 % to 18.3 % with an average value of 17.7 %. The final compost obtained from each type of heap was odorless and black in colour. Chemical analysis of the final compost was carried out for all the heaps. Replicates of each heap yielded compost of near identical quality highlighting consistency of the process. However, significant variation in terms of final compost quality was observed for different heap types (Table S3). Absence of paddy straw (15.8 %) which had a significantly less moisture content compared to cow dung (80.6 %), or water hyacinth (85 %) resulted in lower yields of compost for Heap 2 and Heap 4. Aerobic composting under optimal conditions consists of three distinctive phases viz. the mesophilic phase, the thermophilic phase and maturation phase. Biodegradation begins with the breakdown of soluble organic matter such as starch, monosaccharide, protein, etc. by microorganisms present in the microbial consortia during this mesophilic phase. These microorganism multiply rapidly while degrading the readily available sugars and amino acids and generate heat by their own metabolism. As the heap temperature rises to about 40 °C the activities of mesophilic microorganisms get suppressed and they are replaced by heat-loving thermophilic microorganisms. During the thermophilic phase, high temperatures accelerate the breakdown of complex carbohydrates like cellulose and hemicellulose. The absence of paddy straw significantly reduces the cellulose and hemicellulose content of the heap which may be the reason thermophilic phase was not observed distinctively in the case of Heap 2 and Heap 4. Three distinctive phases of aerobic composting viz. mesophilic, thermophilic, and maturation phase were distinctly observed for Heap 1 and Heap 5 which is indicative of efficient composting process. The highest temperature of 79.2 °C was observed for Heap 5 followed by Heap 1 where the highest recorded temperature reached 69.3 °C. The compost yielded from Heap 1, which was made of only 60 kg (fresh weight) of water hyacinth biomass though was not meeting the organic carbon content, total nitrogen content as per the FCO norms highlighting the importance of identifying the optimal ratio to improve final compost quality. For the Heap 3, which had an initial paddy straw content of 10 kg, the highest temperature of 63.2 °C was recorded though the onset of the thermophilic phase was late for this heap compared to Heap 1 and Heap 5. The cellulose and hemicellulose both are high-energy compound and their content being highest in Heap 5, an early onset as well as prolonged thermophilic phase was observed for Heap 5. A prolonged thermophilic phase is desired to ensure removal of pathogens (*Escherichia coli* and *E. aerogenes*) during the composting process. Because temperatures over about 65 °C kill many forms of microbes and limit the rate of decomposition, manual turning of compost heaps are essential to improve process efficiency. As the supply of high-energy constituents in the heaps get exhausted the heap temperatures gradually decreases and mesophilic microorganisms once again take over for the final phase of "curing" or maturation of the remaining organic matter. High organic content and appropriate carbon/nitrogen (C/N) ratio are indicative of good quality compost. The Fertilizer Control Order (FCO) standard for C/N ratio was <20 and the final compost prepared for Heap 1, Heap 2, Heap 3 and Heap 5 were within this standard limit. The highest organic carbon concentration was observed for the final aerobic compost prepared for Heap 5 and the compost obtained from this heap was found to be in compliance with FCO standards (Table 2). Overall, the study found that Heap 5 represents an optimal ratio of different constituents in terms of final yield as well as quality of compost. Heap 5 was made up of 70 kg (fresh weight) water hyacinth biomass, 20 kg (fresh weight) paddy straw, 10 kg (fresh weight) cow dung and 0.1 kg of microbial culture. Hence, for subsequent bulk production of aerobic compost shredded water hyacinth biomass, shredded paddy straw and fresh cow dung were mixed in the ratio of 7:2:1 for aerobic composting. Compost process reached stabilization within 65 days, maintaining moisture content and periodic heap-turning was found to be critical to ensure efficient composting.

3.3. Large scale composting of water hyacinth biomass

As highlighted in Section 2.3, the water hyacinth biomass was harvested from the infested village pond nearby and cost of the biomass was Rs. 1277 (~ $15) per ton. Paddy straw biomass and cow-dung were both obtained from the local farmers and a bulk rate of Rs.1500 per ton (~ $18) was agreed upon for each after the village level meetings. Local sourcing of raw material through consultation with local stakeholders was done to ensure long-term sustenance of the rural enterprise beyond the project period, distribution of revenue among higher number villagers and higher local ownership of the interventions among the villagers. A total of 25 heaps were prepared each containing about 4–5 tons of mixed biomass. Periodic watering and heap turning was carried out every 12 days. Samples were collected from each heap of compost prepared for this bulk production and average C/N ratio of 17.1 and organic carbon content of 14.6 mg/kg. Samples of the compost prepared were collected and sent for physico-chemical analysis. The analytical data presented in Table 2 highlights that the compost prepared was in compliance with the FCO standard (Table S4). Bulk production of water hyacinth compost in a village involving local stakeholders provided an opportunity to estimate real cost of production considering material cost, heap preparation and maintenance cost, sieving, weighing and packing cost (Table 3). At a bulk scale cost of production for 1 ton of aerobic compost using water hyacinth biomass mixed with paddy straw and cow dung in the optimal ratio was Rs. 7935 which roughly translates

Table 2
Physical and chemical characteristics of aerobic composts prepared.

Parameters	Unit	Heap numbers					FCO standard
		Heap 1	Heap 2	Heap 3	Heap 4	Heap 5	
pH		7.2	6.9	6.84	6.9	7.1	6.5–7.5
Moisture content	mg/kg	172	183	174	181	176	15–25 (City compost) 15–20 (Vermicompost)
C/N ratio		16.39	16.14	15.9	25.4	16.94	< 20
OC %	mg/kg	11.9	10.8	12.93	13.67	14.1	12 (City compost) 18 (Vermicompost)
Total-N	mg/kg	7258	6689	8123	5365	8323	8000 (City compost) 10,000 (Vermicompost)
Total-P	mg/kg	3024	3182	3234	2893	4014	4000 (City compost) 8000 (Vermicompost)
Total-K	mg/kg	4097	4792	4367	4265	4487	4000 (City compost) 8000 (Vermicompost)
Total-Ca	mg/kg	12,789	11,864	10,352	8539	11,789	
Total-Mg	mg/kg	3954	4021	3782	2649	4062	
Total-Fe	mg/kg	6354	5932	6012	4947	5328	
Total-Cu	mg/kg	7	5	4	2	4	
Total-Mn	mg/kg	405	356	253	268	345	
Total-S	mg/kg	2213	2345	2753	2769	2034	
Total-Zn	mg/kg	81	74	61	52	74	1000
Total-B	mg/kg	31	29	24	22	17	
Total-Na	mg/kg	1412	1328	1321	1231	1278	

as Rs.8 per kg Cost of raw materials contributed more 50 % in this cost of production. The labour cost involved in the process highlights local livelihood opportunities for the villagers. As part of several ongoing rural development schemes such as MGNREGA, Swatch Bharat Mission, Pradhan Mantri Adi Adarsh Gram Yojna (PMAGY) water hyacinth harvesting is undertaken for rural surface water bodies particularly for irrigation canals. Hence, water hyacinth biomass can be made available for rural SHGs engaged in aerobic composting of this biomass. This highlights that potential exists for further reduction of the production cost by adopting synergistic approach and linked up the rural enterprise created with various ongoing governmental schemes. It is worth mentioning that for bulk quantities sieving and packaging both are optional and depend on the final quality of the compost at the end of maturing phase as well as customer preference. This highlighted that pricing needs to be different for bulk and retail sale of the aerobic compost to optimize the profit as rural enterprise. A total of 35 tons of aerobic compost was prepared using the biomass harvested from the 2.76-acre pond and retail sales were kept at Rs.10 per kg keeping a profit margin of Rs.2 per kg To ensure consistency in quality sieving was done for the entire quantity. However, packaging was not required for most of the produce as local farmers were keen to take up tractor loads of compost from the production site to their agricultural fields on their own for a reduced cost of Rs.9 per kg Without packaging the production cost was Rs.7035 per ton. A total of 32 tons of compost was sold for Rs.9 per kg fetching a net profit of Rs.1965 per ton. The balance of 3 tons of compost was sold in retail mode to various tourists and visitors as 5 kg jute bags. The total cost of production, revenue obtained, and net profit were Rs. 248,932, Rs. 291,000 and Rs. 42,068 respectively.

Table 3
Cost of production of 1 ton water hyacinth based on aerobic compost.

	Cost component Material			
Raw Material Cost (Fresh weights)	Item	Quantity (kg)	Rate (Rs/kg)	Cost (Rs)
	Water Hyacinth	2047	1.27	2599
	Paddy straw	585	1.5	877
	Cow Dung	292	1.5	439
	Microbial Culture	3	140	420
	Sub-Total (M)	2927		4335
Cost component Labour		Quantity (No.)	Rate (Rs./ day)	Cost (Rs)
HumanLabour cost	Heap preparation (labour cost)	**3**	450	1350
	Heap watering and turning (labour cost)	1	450	450
	Sieving (labour, power)	1	450	450
	Weighing and Packaging (labour)	3	450	1350
	Sub-Total (L)	8	450	3600
	Total ($M + L$)			7935

3.4. Sensitivity analysis

There are important contextual variables such as scale of production, location and access to feedstock that have an important bearing on the economic viability and profitability of compost production [25]. Water hyacinth biomass composting in the present study region is most promising but least undertaken. Usually, ineffective collection and management of water hyacinth biomass will lead to water pollution. What is lacking in the current literature is demonstrable evidence of the economic benefits in water hyacinth biomass composing in India which may enhance confidence among different stakeholders about incentivizing such enterprises. We attempted to do a sensitivity and revenue analysis below adopting methods outlined by [26]. Economic costs and benefits are often easier to identify and measure as they are the direct costs and benefits associated with the production of the output of interest [27]. The economic cost variables for compost production in the present scenario would depend on labor cost and input cost mainly and on fuel cost marginally (Sutton et al., 2020). We may ignore costs such as compost testing and laboratory analysis, depreciation of machinery etc. this being the first batch of compost. The total cost of equipments supplied to the rural enterprise was Rs.153,000, which may be considered as the capital cost. Here labor as well as raw material costs are variable which may impact the profitability of the rural enterprise. The price of 1 kg of compost was fixed as 10 rupees after the market analysis while the production cost of Rs. 8 per kg was computed based on the material cost and operational costs (Table 3). The profit margin of 20 % highlights the economic feasibility of water hyacinth compost production, making it a sustainable alternative for organic farming. The break-even price was found to be 8 per kg, meaning that as long as the market prices remain above this threshold, production remains profitable. The net profit, profit margin and break-even price were computed for 35-ton aerobic compost prepared over a period of 65 days, these were Rs.42,074, 14 % and 7112 per ton respectively. Sensitivity analysis was carried out considering two possible scenarios [28]. For scenario 1, the impact of input cost fluctuations of ±10 % was analyzed and altered profit margins were varied from Rs.26,895 to Rs. 57,241. The difference between for highest (37.4 %) and lowest (17.6 %) net profit margins considering return on capital expenditure was 19.8 % in this scenario. For scenario 2, the impact of output cost fluctuations of ±10 % was analyzed and altered profit margins were varied from Rs.12,967 to Rs. 71,168. The difference between for highest (46.5 %) and lowest (8.5 %) net profit margins considering return on capital expenditure was 38 % in this scenario. The sensitivity analysis suggests that output price fluctuations have a greater impact on profitability than input cost variations, indicating the importance of stable pricing [29]. As each of the scenarios yield a net profit, even for sensitivity analysis based on pessimistic assumptions, investing in a rural enterprise producing water hyacinth based aerobic compost small-scale rural enterprise would lead to revenue generation with additional social and environmental benefits.

3.5. Carbon credit of water hyacinth biomass utilization for aerobic composting

Based on the moisture content as well as carbon and total nitrogen content of the paddy straw and water hyacinth biomass involved in the field scale work presented above carbon credit computation was estimated considering the 'cradle to grave' system boundary and carbon credit of different interventions shown in Fig 6. In absence of the intervention the harvested water hyacinth as well as paddy straw would have been subjected to open burning. The carbon credit hence was calculated from the organic content of the plant biomass as the interventions facilitate recycling of carbon to soil preventing their release in the atmosphere through open burning as carbon dioxide (Table 4). As the compost produced also contains nitrogen, application of compost as soil amendment reduces the application of urea. Carbon footprint of chemical fertilizers such as urea is well documented and 1 kg Urea is equivalent to 0.2 kg C. Considering the above factors total carbon credit computed for 1 ton of water hyacinth compost thus prepared was 1024.22 kg CO_2 equivalent. Compost preparation process involved shredding and sieving and carbon footprint for the production of 1 ton of water hyacinth compost was calculated (45 kg CO_2 equivalent) from the operational data and machine specifications for tractor, shredder, sieving machine etc. As per IPCC guideline the greenhouse gas emissions from compost heaps should be considered as biogenic emissions hence these were ignored during the carbon credit calculations (IPCC, 2006). Net carbon credit of 1 ton of water hyacinth compost was obtained by subtracting the total carbon footprint of the operation from the total carbon credit of the intervention which was 979.2 kg CO_2 equivalent or 0.9792 carbon credit (one carbon credit is worth one tonne of CO_2 equivalent). Considering the price of 1 carbon credit as Rs.850 (~$10), per ton of water hyacinth compost production should fetch Rs.832.32 which is approximately Rs.1 per kg Hence, considering the carbon credit the net cost of production for water hyacinth compost would be Rs.7 per kg (Fig. 7).

4. Conclusion

The work presented demonstrated that the optimal ratio of water hyacinth biomass, paddy straw and cow dung for aerobic composting is 7:2:1 considering cost of raw materials, time taken during the composting process and final compost quality. The cost of production was found to be Rs. 8 per kg and net profit of the rural enterprise was found to be more dependent on stability of the target sale price of Rs.10 rather than fluctuations in input cost. Net carbon credit found to be Rs.1 per kg of water hyacinth compost prepared. Overall, large scale water hyacinth based aerobic composting was found to be a profitable business model when undertaken near the infested water body involving rural SHGs. A stable procurement price for this compost which was found in compliance with FCO norm as would not only create alternative livelihood opportunities while improving ecosystem services but would also help to unlock the revenue generation potential of rural ponds though pisciculture and allied activities. Under various schemes, bulk procurement of farm yard manure (FYM) is undertaken for example in mangrove

Table 4
Net Carbon Credit for 1 ton Water hyacinth compost (WHC).

Carbon Content of WH and Paddy Straw					
Item	Fresh weight (kg)	Dry weight (kg)	C in dry mass (%)	Carbon content (kg)	Total CO_2 Equivalent (kg) (1 kg $C = 3.67$ kg CO_2)
Water Hyacinth Biomass (Moisture: 85 %)	2047	307	29.51	91	333
Paddy straw (Moisture: 15.8 %)	585	492	36	176	647
Sub-Total (OC)	2632				980
Item	Fresh weight (kg)	Nitrogen content (kg)	Urea (46.8 % N) Equivalent (kg) (1 kg Urea = 0.2 kg C)	Carbon Content (1 kg Urea = 0.2 kg C)	Total CO_2 Equivalent (kg) 1 kg $C = 3.67$ kg CO_2)
Urea Equivalent					
Water Hyacinth Biomass (Moisture: 85 %; N: 9.18 %)	2047	28	59.82	12	44.2
Total carbon credit					1024.2
Carbon Footprint Components					
Shredding					
Item	Quantity (kg)	Time Taken by Tractor (60 HP) operated Shredder (h)	Diesel consumption for static operation (8 L/h)	Organic carbon content of Diesel (1 $L = 0.73$ kg C)	Total CO_2 Equivalent (kg) (1 kg $C = 3.67$ kg CO_2)
Water Hyacinth Biomass	2047	1.36	11	7.97	29.25
Paddy straw	585	0.39	0.33	0.12	0.43
Sub-Total (S1)					29.68
Item	Quantity (kg)	No. of tractor trips (1500 kg/trip)	Diesel consumption (@ 2 L per trip)	Organic carbon content of Diesel (1 $L = 0.73$ kg C)	Total CO_2 Equivalent (kg) (1 kg $C = 3.67$ kg CO_2)
Paddy straw	2047	1.36	2.73	1.99	7.31
Cow dung	292	0.19	0.39	0.28	1.04
Sub-Total (T)					8.36
Sieving					
Item	Quantity (kg)	Time taken by 1 HP motor powered electrical sieving machin	0.2234 kg C/hour	Total CO_2 Equivalent (kg) (1 kg $C = 3.67$ kg CO_2)	
Mature compost heap	1000	8	1.79	6.56	
Total Carbon Footprint (kg C)					45
Net CO_2 Equivalent (kg)					979.2

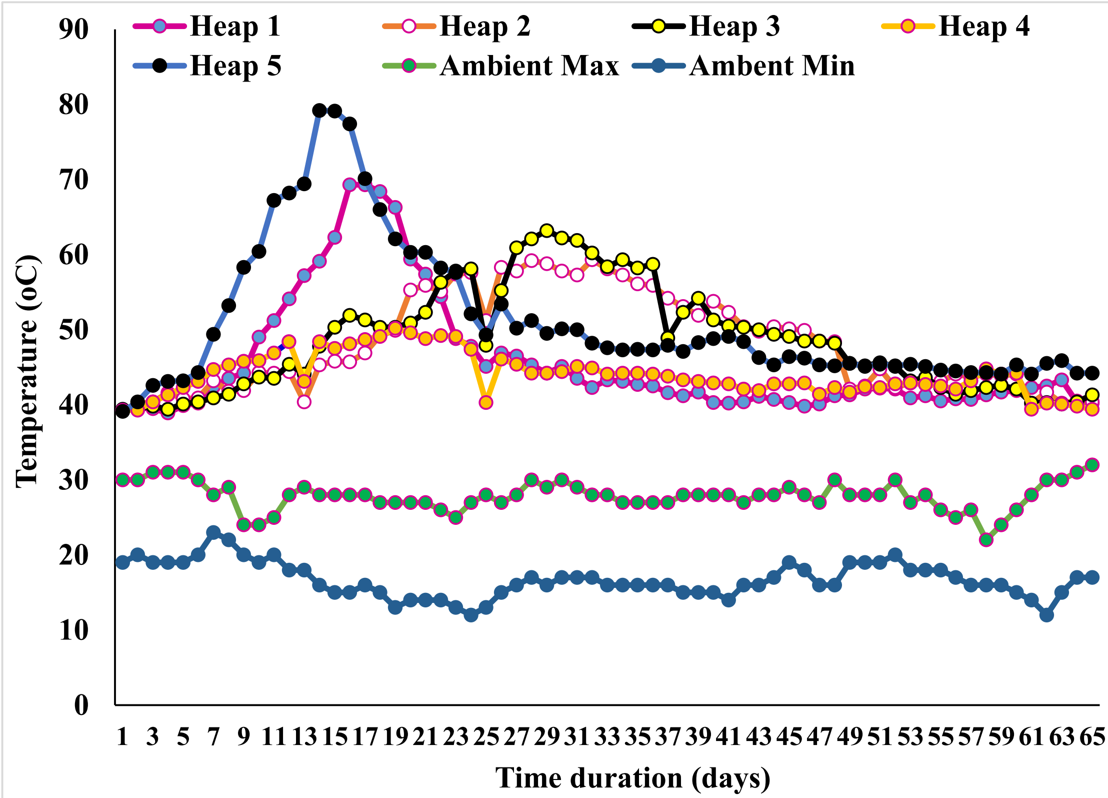

Fig. 7. Temperatures observed during the 65 days for different heaps; (A) Heap 1;(B) Heap 2; (C) Heap 3; (D) Heap 4; (E) Heap 5.

restoration projects, in coffee garden expansion projects, soil health improvement initiatives. Availability of bulk quantities of good quality FYM has been a challenge. Water hyacinth compost which has been named as 'Jalaja Poshak' by the Department of Agriculture, Govt. of Odisha offers a better alternative to FYM.

CRediT authorship contribution statement

Aviraj Datta: Writing – review & editing, Writing – original draft, Visualization, Project administration, Funding acquisition, Data curation. **Hari Om Singh:** Writing – original draft, Data curation. **Santhosh Kumar Raja:** Writing – original draft, Formal analysis. **Ramesh Singh:** Supervision, Conceptualization. **Mangi Lal Jat:** Visualization, Supervision, Conceptualization. **Arabinda Kumar Padhee:** Supervision.

Declaration of competing interest

The authors do hereby declare the following:

1. The work described has not been published previously at all in any form.
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3. The article's publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out.
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Supplementary materials

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Data availability

Data will be made available on request.

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