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Valorization of sorghum residues through vermicomposting and biochar production and their physico chemical characterization

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Abstract
Sorghum residues utility as a livestock feed is rapidly waning and thus is available for alternates uses especially value-added products (valorization). *Rabi* sorghum mega variety 'M-35-1' residues conversion into vermicompost and biochar and their physico-chemical characterization was assessed at ICAR-Indian Institute of Millets Research, Rajandra nagar, Hyderabad, India during 2022. Results indicate that sorghum residues have higher biochar conversion ratio (37.2%) than vermicompost (33%), however, vermicompost has moderately alkaline pH (8.41) while biochar has alkaline pH (9.73). Though both products fell into moderately saline category, EC of vermicompost is higher than biochar (3.76 v 2.61 dSm^{-1}). Bulk density & particle density (g cm^{-3}), porosity and moisture holding capacity (%) has increased by 14.2, 16.2, 1.42 and 1.89 times (vermicompost) and 2.16, 4.27, 1.99 and 10.9 times (biochar) as compared to sorghum residues. Carbon concentration is reduced by 25.7% in vermicompost production but increased by 43.8% in biochar production and biochar falls into Class 2 as per International Biochar Initiative (IBA). Elemental composition indicates that vermicompost is enriched by 468, 100, 42.9, 24.4, 32.3, 147, 13.7, 44.8 and 103% for N, P, K, Ca, Mg, S, Cu, Mn and Na while biochar in N, K, Ca, Mg, Fe, Zn, Cu, and Mn by 144, 24.2, 80.0, 8.82, 246, 790, 662, and 36.2%. However, there is reduction in Fe & Zn (81.6 and 34.5%) and P and S contents (48.3 and 53.3%) in vermicompost and biochar as compared to sorghum residues. Sorghum residues (₹ 3000/ ton) valorization into vermicompost and biochar involve additional expenditure of ₹ 4350 and 2500/ ton and a selling price of ₹ 9.2 and 8.1 per kg is cane be marketing price and an agro-industry can thrive on it. Vermicompost can be used in organic nourishment of crops while biochar in enhancing soil moisture storage in dry lands and in long-term C sequestration.

Keywords: Biochar, vermicompost, sorghum residues, valorization, carbon

Introduction
Millets are inevitable staples cultivated by farmers in moisture and nutrient stressed agro-ecologies *i.e.*, in arid and semi-arid regions. On such ecologies with vertisols, *rabi* sorghum cultivation is done in India. High temperature and low precipitation of these regions leads to depletion of soil organic carbon (SOC) on account of its accelerated breakdown (Post *et al.*, 1982) [24] and climate change associated temperature increases are further reported to accelerate this loss (Kirschbaum, 1995) [12]. Long term studies on *rabi* sorghum cultivation in vertisols of India (Srinivasarao *et al.*, 2012) [33] indicated that 1.1 t/ha of SOC addition is required to maintain the current level of C in soil. FYM, and crop residues application along with fertilizers was able to improve the SOC and for every ton increase in SOC, sorghum crop yields improved by 0.09 t/ha (Srinivasarao *et al.*, 2012) [33]. Direct addition of crop residues though improves SOC, it is associated with immobilization of nutrients especially N on account of its high C: N ratio (60:1) and calls for additional N fertilizer dose to counter the immobilization effects. Further, organic acids are produced during decomposition of residues (Guenzi and McCalla, 1966) [9] that hampers germination and growth of crops. Further, addition of residues may invite many insects, especially termites (Okwakol, 1989) [21] that can damage the crop roots and their successful establishment. In this context, vermicompost and biochar production from sorghum residues (valorization) before soil application is promising.

Valorisation is the act of making an existing substance something valuable or useful. Valorisation of agricultural residues is gaining attraction across multiple domains i.e. for bio energy production (biochar, biogas and bio ethanol), organic soil amendments (vermicompost and compost) and biochemical extraction (lignocellulosic bio-refinery and phenolic compounds), pellets & briquettes etc. Millets especially sorghum and pearl millet generates huge quantities of residues including panicle chaff. Sorghum is cultivated during both *kharif* and *rabi* seasons on 3.8 m ha (in 2023) in India and is estimated to generate 10.56 m t of residues i.e. 7.48, 0.88 and 2.2 m t of stalks, husk and cob (Chauhan *et al.*, 2022) [4]. As sorghum residues utility as livestock feed is rapidly waning on account of reducing draught animals (24.43% decline between 2012 (74.02 million) and 2019, as per Livestock Census data of India) and increasing number of milch animals, with the later relying heavily on green fodder and concentrates. In this context, major quantity of sorghum residues is available for valorisation that is the need of the hour. However, little information on valorization of sorghum residues into vermicompost and biochar is available. Hence, the present investigation was carried out to produce vermicompost and biochar from sorghum residues, characterize them for physico-chemical traits besides working out the economics.

Materials and Methods

The present investigation was carried out at the ICAR- Indian Institute of Millet Research, Rajendra nagar, Hyderabad, Telangana, India. Crop residues generated from a field study with recommended dose of fertilizers during *rabi* 2021-22 season from 'M-35-1' were used. Sun dried sorghum residues after grain separation (stalk, leaves, panicle chaff) were used in valorisation. Sorghum residue was finely chopped into powder and cut into pieces of about 15 cm and were used for vermicompost and biochar production.

Vermicompost production was done in UV treated grow bags of 36"x12"x12" size of 200 GSM thickness into which 10 kg of finely chopped residue powder was filled (Figure1). The surface feeding earthworm '*Eisenia fetida'* from Vermicompost unit in the College Farm at Professor Jayashankar Telangana Agricultural University (PJTAU) of 750 grams was released into grow bag. Three bags (replication) were kept for vermicomposting. At the base of vermiculture bed, water was sprinkled first and alternating layers of residues and FYM was spread by sprinkling water at each layer and the earthworms are slowly released into the bed. The grow bag was placed in shade and sprinkled water twice a day to maintain sufficient moisture and the vermiculture beds were mixed properly for every 15 days so that mixing ensures aeration of beds. After complete decomposition of residue, it turned into dark brown to black colour, light in weight and with earthy smell and it took in 90 days. Watering was be stopped one week before harvesting vermicompost, and then dried, sieved and stored.

Sorghum biochar was prepared in fixed-type annual core reactor obtained from ICAR-Central Institute of Agricultural Engineering (CIAE), Bhopal, Madhya Pradesh. The feedstock material was fed into the biochar reactor unit and heated at a pyrolysis temperature of 400ºC. The biochar reactor reached 400ºC approximately in one hour and 30 minutes residence time was maintained and after 24 hours the biochar was collected and weighed.

Conversion ratio of residues into vermicompost and biochar was estimated as weight ratio of vermicompost or biochar to the weight of residues used. Physico-chemical characterization for pH, EC, bulk density, particle density, porosity and water holding capacity was carried out at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, PJTAU, Rajendra nagar, Hyderabad. Based on organic carbon content, biochar was classified into (IBI-STD-01.1; IBI-STD-2.0) as per the International Biochar Initiative (IBI) (IBI, 2014) [14] and pH of residue, vermicompost and biochar were classified as per USDA. The elemental composition estimations of biochar were done at Central Instrumentation Cell, PJTAU and ICAR-Central Institute of Dryland Agriculture (CRIDA), Hyderabad and vermicompost in Fertiliser Control Order (FCO) Laboratory, Rajendra nagar. Economics for the production of vermicompost and biochar was also carried out. Statistical analysis was carried out in Fisher's Least Significant Difference (LSD) test for physico-chemical parameters and elemental composition.

Results and Discussion

The results pertaining to the conversion ratio of valorized products of sorghum residue, their physico-chemical parameters, elemental composition and economics for the production of valorized products is presented here. Sorghum residues conversion into vermicompost and biochar was presented in Figure 1 and annual core biochar unit is presented in Figure 2.

Fig 1: Sorghum crop residues converted into vermicompost and biochar

Fig 2: Annual core biochar unit

Conversion ratio (%) and physico-chemical properties

Data on sorghum residues conversion ratio into two valorized products and their physico-chemical properties is presented in Table 1. Data reveals that sorghum residues have a mean vermicompost and biochar conversion ratio of 33.0 and 37.2%. Our vermicompost conversion ratio values were higher than that of Savant (2016) [28] and Sharma *et al.* (2020) [30], who obtained 19.0 and 25.0% yield recovery from sorghum and rice straws + cow dung. Dominguez (2004) [7] found that during the process of composting, earthworms reduced the volume of raw material by 40-60%. Our biochar conversion ratio values were comparable with those reported of Kocer *et al.* (2018) [13] i.e. 33.0% with sweet sorghum residues at similar pyrolysis temperature (400°C) and a residence time (30 minutes) as ours.

Table 1: Physico-chemical properties of sorghum residue, vermicompost and biochar

	Residue	Vermicompost	Biochar	CD value
Conversion ratio (%)	100.0	33.0^{b}	37.2^{a}	3.14
pH	7.90^{c}	8.41^{b}	9.73^{a}	0.19
EC (dS m^{-1})	1.82^{c}	3.76^{a}	2.61^{b}	0.16
Bulk density (g cm^{-3})	0.06^{c}	0.85^{a}	0.13^{b}	0.06
Particle density (g cm^{-3})	0.11^{c}	1.78^{a}	0.47^{b}	0.07
Porosity (%)	36.70^{c}	52.2^{b}	73.2^{a}	4.98
Moisture holding capacity (%)	31.3^{c}	59.3^{b}	343^{a}	12.2

Mean pH of sorghum biochar (9.73) is significantly higher than the vermicompost (8.41) while for EC, the converse is true with vermicompost having higher EC values (3.76 dSm^{-1}) than biochar (2.61 dSm^{-1}). As per USDA classification based on pH, vermicompost and biochar are classified as moderately alkaline and alkaline and based on EC values, both vermicompost and biochar were classified as moderately saline. Valorization of sorghum residue has increased the pH and EC of vermicompost by 0.51 and 1.94 units and biochar by 1.83 and 0.79 units. Similar pH (8.43) and EC (3.29 dSm^{-1}) values of sorghum residue vermicompost were reported by Geremu *et al.* (2020) [8]. Our biochar pH values were slightly higher than those reported by Ogunremi *et al.* (2023) [20] who used higher pyrolysis temperatures (500°C) than ours, however, our EC values were consistent with Yin *et al.* (2022) [36] who produced maize biochar. High-temperature conditions (over 300°C) cause an increase in pH due to organic acid decomposition, alkaline salt production and release from ash, and volatile component elimination, all of which contribute to biochar alkalinity (Lee *et al.*, 2024) [17]. The rise in soluble salt concentration, such as K and Na, might be the reason for increase in biochar EC (Azargohar *et al.*, 2014) [2].

Bulk density of vermicompost (0.85 g cm^{-3}) is significantly higher than biochar (0.13 g cm^{-3}) and least in residue (0.06 g cm^{-3}). Bulk density of vermicompost and biochar are 14.2 and 2.17 times higher than sorghum residue. Vermicompost being more compact due to the reduced volume in the decomposition process and inclusion of earthworm castings that were lighter to sorghum residue resulted in higher bulk density of vermicompost than residues. Our results are consistent with the findings of Singh *et al.* (2023) [32] who reported a bulk density of sorghum biochar (0.74 g cm^{-3}) that was slightly lower than our values (0.85 g cm^{-3}). Higher bulk density of biochar attributes to pyrolysis process used to transform the original biomass has reduced its volume (conversion ratio of 37%) thus increased bulk density. Particle density of sorghum residue vermicompost (1.78 g cm^{-3}) was significantly higher than biochar (0.47 g cm^{-3}) and lowest for residues (0.11 g cm^{-3}). Particle density of sorghum residue vermicompost and biochar is 16.2 and 4.27 times higher than residue. Our sorghum biochar particle density results are consistent with the results of Rajyalaksmi *et al.* (2024) for pearl millet biochar and of da Silva *et al.* (2017) [31] for sorghum biochar. Porosity of biochar (73.2%) is significantly higher than vermicompost (52.2%) and least in residue (36.7%). Porosity of valorized vermicompost and biochar was 1.42 and 1.99 times higher than residue. The porous structure of biochar contributes to its higher particle density (Brewer and Levine, 2015) [3]. Moisture holding capacity of biochar (343%) is 1.89 and 10.9 times higher than vermicompost (59.3%) and sorghum residue (31.3%). Higher porosity of vermicompost and biochar leads to higher moisture holding capacity. During the decomposition process, organic matter breaks down into peat-like material with high proportion of pore spaces which in turn has the ability to hold high amount of moisture in it. During biochar production, decomposition of organic matter and formation of micropores results in higher pore space (Tomczyk *et al.*, 2020) [35] thus increasing the moisture holding capacity. Our results are consistent with the findings of Sanborn *et al.* (2017) [26] who observed 750% higher moisture holding capacity in sorghum biochar.

Table 2: Elemental composition of Residue in comparison to vermicompost and biochar

Element	Residue	Vermicompost	Biochar	CD
C (%)	36.5^{b}	27.1^{c}	52.5^{a}	3.96
N (%)	0.48^{c}	2.73^{a}	1.17^{b}	0.09
P (%)	0.29^{b}	0.58^{a}	0.15^{c}	0.05
K (%)	1.28^{c}	1.83^{a}	1.59^{b}	0.14
Ca (%)	0.45^{c}	0.56^{b}	0.81^{a}	0.06
Mg (%)	0.34^{b}	0.45^{a}	0.37^{b}	0.05
S (%)	0.15^{b}	0.37^{a}	0.07^{c}	0.06
Fe (ppm)	307^{b}	56.4^{c}	1061^{a}	10.7
Zn (ppm)	31.8^{b}	20.8^{b}	283^{a}	14.9
Cu (ppm)	10.2^{b}	11.6^{b}	77.7^{a}	5.19
Mn (ppm)	45.0^{b}	65.2^{a}	61.3^{a}	5.42
Na (ppm)	985^{b}	2003^{a}	1012^{b}	62.8

Elemental composition of valorized sorghum residues

The elemental composition of valorized sorghum residue products was presented in Table 2. Valorization of residue (36.5%) has decreased the C concentration of vermicompost (27.1%) but has increased it in biochar (52.5%). Mean C concentration is significantly higher in biochar than the residues and was least in vermicompost. According to IBI classification, based on C content (30-60%), our biochar is classified as class-2 (IBI, 2014). The increased C in biochar attributes to the depletion of hydrogen and oxygen during the pyrolysis (Zeng *et al.*, 2018) [37]. Our results of C content in vermicompost are consistent with the findings of Sawargaonkar *et al.* (2013) [29] and for sorghum biochar with Ogunremi *et al.* (2023) [20].

Primary nutrients (N, P and K) concentration indicates that vermicomposting of sorghum residues on an average resulted in 5.69, 2.0 and 1.43 times enrichment in N, P and K while biochar making resulted in 2.44 and 1.24 times enhancement in N and K concertation while there is 48.3% decline in P concentration. Higher N, P and K concentrations in the vermicompost attributes to the decomposition of organic matter, enzymatic activity in earthworm's gut (Savant, 2016) [28] and transformation of elements from organic to inorganic state (Lakshmi *et al.*, 2013) [16]. Our results are comparable with N (1.15%), P (0.63%) and K (0.95%) contents in sorghum vermicompost reported by Savant (2016) [28] though N and K are lower than our values.

Valorization of sorghum residues into vermicompost has resulted in significant increase of Ca, Mg and S concentration however, biochar making has improved Ca concentration but substantially decreased S concentration. On an average, vermicompost has 24.4, 32.3 and 147% higher Ca, Mg and S and biochar has 80% higher Ca concentration (53.3% lower S) than sorghum residues. The biological activity and transformation processes involved in vermicomposting contribute significantly to the rise in Ca and Mg concentrations in vermicompost during the conversion of residue into vermicompost (Olle, 2019) [22]. Our results are consistent with Geremu *et al.* (2016) [8] who reported 0.68% Ca in sorghum residue vermicompost but lower Mg (0.15%) concentration than ours while S concentration was comparable with Savant (2016) [28] who reported a S concentration of 0.48%.

Valorization of sorghum residue into vermicompost has reduced Fe and Zn concentration by 81.6 and 34.5% but has increased Cu, Mn and Na concentrations by 1.13, 1.45 and 2.03 times. However, conversion of sorghum residues into biochar has increased concentration of Fe, Zn, Cu and Mn by 3.45, 8.89, 7.61 and 1.36 times but Na concentration remained unaffected. The increase in micronutrient concentration in the vermicompost attributes to the progressive mineralization of organic matter and losses through respiration of earthworms during composting process (Amir *et al.,* 2005; Lv *et al.,* 2016) [1, 19]. Low Fe and Zn concentrations of vermicompost might be due to the bio-accumulation of in the earthworm tissues (Suthar and Gairola, 2014) [34]. Our elemental composition results of vermicompost are consistent with the findings of Pawar *et al.* (2016) [23] and with the findings of Dhyani *et al.* (2017) [6] and Kotaiah Naik *et al.* (2017) [14] for biochar. The elevated micronutrient concentration in biochar might attribute to mass loss in weight at high temperatures during pyrolysis (Sarafaraz *et al.*, 2020) [27]. Burning of organic matter and volatilization of nutrients during the process of pyrolysis attributes to reduction in P and S concentration of biochar (Sarafaraz *et al.,* 2020) [27].

Economics

The cost of valorisation of a ton of sorghum residue (₹ 3000) into vermicompost (residues, earthworms, labour wages, chopping and power consumption, watering) and biochar (residues, labour wages, chopping and power consumption) was ₹ 7350 and 6500. Keeping margin of 25%, a selling price of ₹ 9188 and 8125 per ton makes valorisation of sorghum residues profitable on which agro-industries can be developed. Similar economic gains were reported due to vermicompost production by Devkota *et al.* (2014) [5].

Conclusion

The present investigation clearly demonstrates that sorghum residues can be effectively valorized into vermicompost and biochar. Among the two, biochar exhibited a higher conversion ratio and has greater C content, making it suitable for long-term C sequestration and structural improvement of soil. In contrast, vermicompost proved superior in essential plant nutrients. Both products up on addition to soil can significantly improve the physico-chemical properties of the soil particularly porosity and moisture retention making them beneficial in dryland and nutrient-depleted agro-ecologies. Elemental analysis further confirmed that valorization alters nutrient profiles differently: vermicompost increases macronutrient availability, whereas biochar enhances micronutrient and C concentration. Thus, we can say that vermicompost enhances nutrient supply (can be an organic manure) and biochar can be used as an ameliorant for countering moisture stress through enhanced water storage in soil and C for longer duration Economic evaluation revealed that both processes are cost-effective, with production costs recoverable through marketable pricing, thus presenting a viable income-generating opportunity for farmers.

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