Alternative sources of soil organic amendments for sustaining soil health and crop productivity in India – impacts, potential availability, constraints and future strategies

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Among the several causes, critical low soil organic matter status is predominant for decline in soil health and consequent fall in crop productivity. Over the years, availability of traditional source of soil organic amendment, viz. cattle manure drastically declined due to various reasons (domestic uses as fuel and plastering of the kachha houses). The present study highlights that there are many alternative sources of soil organic amendments available in the country which have tremendous potential to improve soil organic matter status and crop productivity, and rejuvenate and enhance the dying total factor productivity of Indian soils. Data from various sources reveal that about 300 million tonnes of alternative sources of soil organic amendments are available in the country. This study highlights that the application of alternative sources of organic amendments directly or indirectly improves soil health by influencing many soil properties (physical and chemical) and enzyme activities (biological) that regulate nutrient dynamics in the soil. Consequent upon improvement in soil environment, the application of alternative sources of soil organic amendments alone or along with recommended dose of fertilizers registered significantly higher yield in different crops across different agro-climatic conditions of the country. Composting and vermicomposting are the best strategies to convert the biomass of available alternative sources of organic amendments to plant nutrient-rich products.

Keywords: Climate change, crop productivity, organic amendments, soil health.

DECLINE in soil health is an important issue for sustaining crop productivity as well as human health. Research findings of the various long-term fertilizer experiments from intensive cultivated areas of the country (rice–wheat systems) have shown a continuing decline in soil health and in long-term crop productivity due to sole use, overuse and imbalanced use of chemical fertilizers (without organic fertilizers)[1]. It has been established that besides several other factors, low organic matter status of Indian soil is an important cause for decline in soil health and crop productivity[2]. Moreover, intensive tillage and high water requirement mostly linked with high use of chemical fertilizers and their over dependence have degraded the soil health resulting in decline in soil carbon stocks[3]. In the past, in India, policy makers and researchers have focused more on chemical soil health compared to soil physical and biological health for enhancing crop productivity[4]. However, research findings have proved that the physical and biological health of the soil also plays a key role in maintaining its productive capacity of soil and ultimately crop productivity[4,5]. For enhancing crop productivity by improving the overall soil health (physical, chemical and biological), soil organic amendments could be better options, if handled properly by all the stake holders (farmers, Government, NGOs, private sector, researchers, policy makers, etc). Once the overall soil health improves, the response of crops to added fertilizers will also increase. Further, these amendments will also enhance the inherent nutrient status and its availability for plant growth. This in turn will help in reducing the plant demand for chemical fertilizers. It is estimated that in India organic sources contribute five million tonnes (mt) of available nutrients (NPK) annually and this is expected to increase to 7.75 mt by 2025 (ref. 2).

Over the years, however, availability of traditional source of soil organic amendment (cattle manure) has decreased drastically due to its use for other domestic purposes (as a fuel and plastering of kachha houses). According to FAO[2], during the early 1970s, out of the total cattle manure available, 70% was used for fertilizing the crops, while its use decreased to 30% in early 1990s. Further, during 2005, the application rate of farmyard manure was much below (about 2 tonne ha^{-1}) the recommended rate in the soil (10 tonne ha^{-1}). It has been estimated that the increase in soil organic carbon pool of developing countries is to the extent of 1 Mg C ha^{-1} yr^{-1}

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through residues mulching and/or use of other biosolids (alternative sources of organic amendments), whereas the estimated corresponding annual increase in food production is about 30–51 million Mg yr^{-1} (ref. 6). Considering the consequent decline in the availability of traditional sources of organic amendments (cattle manure) and resultant decline in total factor productivity and poor response to chemical fertilizers, other relevant alternative organic sources are necessary to enhance the overall functional capacity of soils to produce adequate food to feed the ever increasing population of the country, and simultaneously to enhance the marketable surplus to increase the net income of the farmers.

Why is soil health crucial for Indian agriculture?

There are estimates that the Indian population, which increased from 439 million in 1960 to 1210 million in 2010, is anticipated to reach 1332.9 million in 2020. Similarly, foodgrain production increased from 82 mt in 1960 to 241 mt in 2010, and is anticipated to reach 294 mt in 2020 (refs 1, 7). At the same time, the fertilizer consumption of India, which was below 1 lakh tonnes in 1960, increased to 268 lakh tonnes in 2010 (ref. 8). However, some conservative estimates reveal that India will require more than 400 lakh tonnes of chemical fertilizers by the year 2020 (Figure 1)[1,7–9]. Although increase in fertilizer consumption has been followed by an increase in foodgrain production over the years, there may not be direct correlation between fertilizer consumption and foodgrain production during each year, since there are a large number of other factors (viz. rainfall, drought, crop management, etc.) which might have affected crop yields on a year-to-year basis[10].

It is a matter of great concern that fertilizer consumption versus foodgrain production has weakened over the years. It is well depicted in Figure 1 that from 1960 to 2007, the gap between fertilizer consumption (lakh tonnes) and foodgrain production (mt) started narrowing down each year. However, after 2008, fertilizer consumption (lakh tonnes) has surpassed foodgrain production (mt) and it is expected that during the coming years, the gap between the two will further widen. Further, the per hectare consumption of fertilizers rose from 1.99 kg in 1960 to 135.33 kg in 2009–10 and continuously showed an increasing trend, while the average crop response to fertilizer use was around 25 kg grain kg^{-1} NPK during 1960s, which declined drastically to only 6 kg grain kg^{-1} NPK fertilizer during the 11th Plan (2007–2012) (Figure 2)[8,9,11]. Thus, on the one hand, India's population is continuously increasing, while on the other hand, despite increase in per hectare fertilizer consumption over the years, in most of our important production systems, total factor productivity is decreasing. This is the crucial issue to be addressed. To date, however, chemical fertilizers still play an important role in enhancing crop productivity in India and around the world[12].

Organic carbon status of Indian soil

According to FAO[2], most of the Indian soils are low in organic carbon content and other plant nutrients; the organic carbon content is less than 1%. The status of soil organic carbon in arid ecosystem, irrigated ecosystem and rainfed ecosystem has become critically low; the value is less than 0.6% in the top 0–30 cm soil depth[13,14]. Bhattacharyya *et al.*[14] reported that among 15 different agro climatic zones (ACZs) in the country, in 10 ACZs the organic carbon content was less than 0.8% in 0–30 cm soil depth (Table 1). The situation is alarming in the Indo-Gangetic plains (ACZs 3–6, Table 1), and Eastern, Central and Western plateau and hills regions (ACZs 7–9, Table 1) where the organic carbon content was less than 0.5% in the top 0–30 cm soil depth. Overall, Indian soils have been graded as 63% low, 26% medium and only 11% high in organic carbon content. Analysis of soil

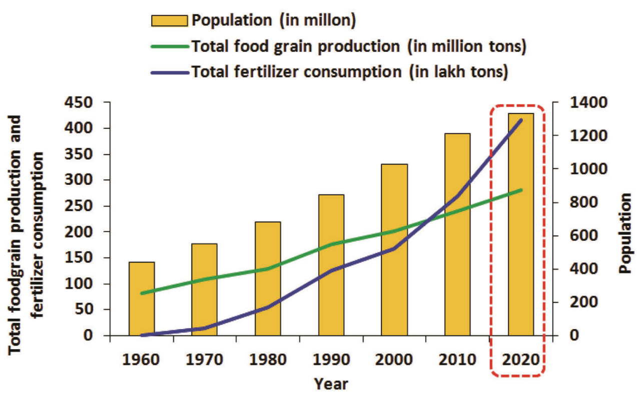

Figure 1. Relationship between the population of India, fertilizer consumption and foodgrain production (estimated using various data sources)[1,7–9].

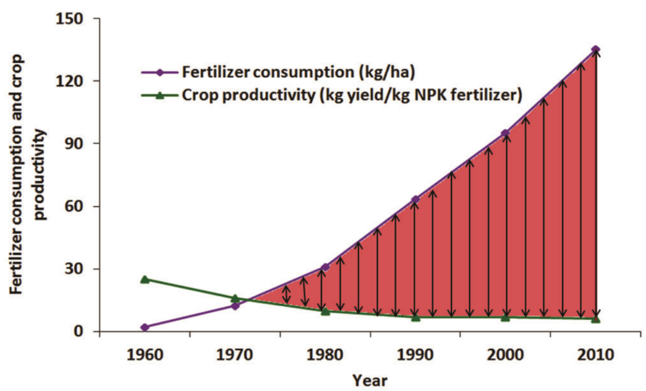

Figure 2. Relationship between per kilogram fertilizer consumption and per kilogram crop productivity (estimated using various data sources)[8,9,11].

samples collected from farmer's fields in different states (Andhra Pradesh, Karnataka, Rajasthan, Madhya Pradesh, Tamil Nadu and Gujarat) revealed that the deficiency of organic carbon content was closely linked to deficiency of other nutrients (P, K, S, B and Zn)[15].

Apart from other factors, some studies have reported that intensification of agriculture has resulted in reduction in the use of organic matter by almost 50% over time, whereas replacement of organic amendments (manure) with chemical fertilizers for decades has also reduced the organic matter content of soils to less than 1% under Indian conditions[16]. Cultivated area of the country has remained constant for the past 30 years (about 141 million ha), but during the same period, cropping intensity has increased from 118% to 135% (ref. 2). Nevertheless, Bhattacharyya *et al.*[17] have reported that for the last 25 years, where appropriate soil and crop management practices have been adopted, there has not been much decline in soil organic carbon in the major growing zones of the country; this in turn has increased the organic C stocks in soil. However, considering the outcome of several other studies, the organic C content in majority of the surface soils in India has declined substantially. Hence to improve the inherently low organic matter content of Indian soils as well as overall soil health and productivity, regular application of sufficient quantities of organic amendments is essential.

Table 1. Organic carbon content at 0–30 cm soil depth in different agro-climatic zones (ACZs) of India*

ACZs	Organic carbon (%) at 0–30 cm on soil depth (mean values)
Western Himalaya Zone ((ACZ 1)	0.67
Eastern Himalaya Zone (ACZ 2)	1.88
Lower Gangetic Plains (ACZ 3)	0.47
Middle Gangetic Plains (ACZ 4)	0.18
Upper Gangetic Plains (ACZ 5)	0.78
Trans Gangetic Plains (ACZ 6)	0.27
Eastern plateau and hills regions (ACZ 7)	0.42
Central plateau and hills regions (ACZ 8)	0.52
Western plateau and hills regions (ACZ 9)	0.49
Southern plateau and hills regions (ACZ 10)	1.22
East coast and plains and hills (ACZ 11)	1.15
West coast plains and ghat regions (ACZ 12)	1.77
Gujarat plains and hills (ACZ 13)	0.63
Western dry (ACZ 14)	0.20
Island (ACZ 15)	6.14

*Data compiled from the Bhattacharyya *et al.*[14] by taking the mean of the different soil series for a particular ACZ.

Table 2. Potential availability of different alternative organic sources in India[18–25]

Alternative organic sources	Total availability/yr	Reference
Crop residues	500–550 million tonnes (mt)	18
Municipal biosolid	48 mt	19
Rice husk	20 mt	20
Sugarcane bagasse	90 mt	20
Groundnut shell	11 mt	20
Sugarcane pressmud	9.0 mt	21
Poultry manure	6.25–8 mt	22
Coir pith	7.5 mt	23
Food/fruit processing industries	4.5 mt	21
Distillation waste from plant materials after extraction of essential oil	2–3 t	24
Seri waste	5000 tonne	25
Willow dust	30,000 tonne	21
Green manuring crop area	About 7 million hectare	2

Alternative source of soil organic amendments – potential availability, impacts and constraints

Numerous alternative sources of soil organic amendments are available to farmers as on-farm materials, viz. crop residue, weed biomass (aquatic and territorial), green manuring, compost, vermicompost, animal bedding materials, seriwaste, etc., and also off-farm sources, viz. agro industries waste, municipal biosolids, poultry manure, coir pith, biochar, tank silt, etc. Studies have shown that 300 mt of alternative sources of soil organic amendments are available in the country (Table 2)[18–25]. These alternative organic sources have the potential to enable us to ameliorate soils and improve crop productivity in the country. The following are some of the alternative sources of the soil organic amendments available in the country.

Crop residues

During the processing of agricultural crops at the time of harvesting, a large amount of residues is generated. These crop residues are used as animal feed, soil mulch, manure, thatching material for rural homes, fuel for domestic and industrial purposes, etc. According to FAO[2], two-thirds of all available crop residues are used as animal feed, only one-third is available for direct recycling (compost-making). Agriculture in India produces about 500–550 mt of crop residues annually[18]. However, a large portion of these crop residues (about 90–140 mt), is burnt annually on-farm, primarily to clear the fields to facilitate sowing of the next crop[26]. Based on a long-term study (2005–2012) by Sharma *et al.*[27] in sorghum–cowpea system in rainfed Alfisol, it was found that the surface application of sorghum residue @ 6 and 4 tonne ha^{-1} increased grain yield by 21% and 16% respectively, compared to control (no residue), whereas the corresponding increase in cowpea yield was 50% and 60% respectively. Similarly, application of dry sorghum residue (2 tonne ha^{-1}) and fresh gliricidia loppings (2 tonne ha^{-1}) showed significant increase in organic carbon by 6.28% and 3.7% respectively, over no residue application[28]. Besides these, other important soil properties such as available N, available K, exchangeable Mg, available S, microbial biomass carbon (MBC), dehydrogenase activity (DHA), labile carbon (LC), bulk density (BD) and mean weight diameter (MWD) of soil aggregates were also significantly improved. Singh *et al.*[29] concluded that incorporation of rice residue for seven years increased organic carbon content of sandy loam soil significantly over the practice of straw burning or residues removal. Further, they reported that wheat straw incorporation increased organic carbon content from 0.40% (in control treatment) to 0.53% (in case of straw incorporation). According to an estimate, rice residue from 1 ha area gives about 3.2 tonnes of manure rich in nutrients as farmyard manure[18]. Crop residues are an important source of organic matter for improving soil health and crop productivity. However, there are some constraints in handling crop residues. These are: (i) inadequate facilities for collection of crop residues because they are bulky in nature, and it is a time-consuming process and labour-intensive activity; (ii) lack of suitable machinery for shredding/mixing of crop residues in the soil, (iii) lack of financial support for composting crop residues, etc. Also, farmers feel that the process of burning boosts the soil fertility and helps in controlling weeds, pests and diseases. Although the burning affects the soil fertility in different manner as it increases the short-term availability of some nutrients (e.g. P, K) and reduces soil acidity, it leads to loss of other nutrients (e.g. N, S) and organic matter, and can also reduce microbial population near the soil surface. Beside these, it is important to mention here that crop residues burning is a potential source of green house gases (GHGs) and other chemically and radiative important trace gases and other hydrocarbons. Consequently, this results in environmental pollution[18].

Aquatic weed biomass

In India, many canals, rivers, water reservoirs, lakes and other water bodies suffer from massive growth of aquatic weeds. Similarly, huge areas of lowland paddy fields in Kerala, Goa and the Northeast region of India are badly infected with aquatic weeds like *Eichhornia crassipes* (water hyacinth), *Salvinia molesta*, *Chara* spp., *Nitella* spp. and algal scum[30]. In India, water hyacinth alone has spread over 2 lakh ha of water surface in perennial rivers, lakes and other water bodies[31]. Water hyacinth can act as a good soil organic amendment (green manure). It leads to soil organic matter build-up by forming valuable source of plant nutrients, which are essential for plant growth. A fresh plant contains 95.5% moisture, 0.04% N, 0.06% P_2O_5, 0.20% K_2O and 3.5% organic matter[32]. Results of a study revealed that maximum value of yield and growth parameters was recorded in eggplant (*Solanum melongena* L.) treated with *Eichhornia*-vermicompost + 50% recommended dose of fertilizers (RDF) and was found superior to cow dung-vermicompost + 50% RDF and 100% RDF[33]. In another study, a significant increase in the percentage of germination, fresh weight, dry weight, biomass, root and shoot length of wheat plants was observed in *E. crassipes*-treated compost compared to control; higher soil moisture and organic matter were also observed in the treated plots[32]. *Eichhornia crassipes* was also successfully used as mulch material in potato crop[34]. Most of the water bodies are situated near the cities or generally far away from the farmers' fields, and hence transport cost is high. The lack of suitable technology to convert the bulky aquatic weed into nutrient-rich compost or liquid fertilizers is necessary on a large scale.

Terrestrial weed biomass

Recycling available terrestrial weed biomass particularly having no fodder value may help enrich the soil environment in the long term. It is reported that the application of 10 Mg ha^{-1} (dry weight basis) weed mulch of wild sage (*Lantana camara*) and eupatorium (*Eupatorium adenophorum*) to the previous standing maize as monsoon rains receded, in combination with conservation tillage, conserved sufficient moisture in the soil surface until sowing of rainfed wheat, maintained more friable soil structure, provided a favourable soil hydrothermal regime for greater root growth and early establishment of the crop, and finally, produced higher grain and straw yields of wheat[4]. In maize crop, basooti weed (*Adhatoda vasica*) biomass used as a mulch, few weeks prior to harvest, increased mean maize yield from 2.3 to 2.6 tonne ha^{-1}, and that of following wheat from 1.9 to 2.3 tonne ha^{-1} (ref. 35). Biradar and Patil[36] successfully prepared vermicompost from various weeds (*Cassia seracea*, *Parthenium hysterophorus*, *Achyranthus aspera*, *Pennisetum* spp. and *Euphorbia geniculata*) and reported that higher vermicompost yield (683 kg/bed) was recorded with *C. seracea* compared to other weeds species. They reported that weeds can be used as a source of organic biomass for vermicomposting, and act as a good source of plant nutrients (Table 3). Suitable technology for converting organic biomass into the vermicompost is essential. Identification of such species for specific ecological niches is a high priority. Moreover, the labour and transportation cost is also high for handling the huge biomass.

Solid organic waste from agro-industries

Large quantity of waste in solid form is generated by agro-based industries, food-processing industries, sugar mills, distilleries industry, etc. (Table 2). The wastes generated from agro-industries are mainly sugarcane bagasse and press mud, paddy husk, wastes of vegetables, food

Table 3. Nutrient content of some vermicomposts prepared from kitchen and agricultural wastes*

Organic sources	Organic carbon (%)	Total N (%)	Total P (%)	Total K (%)	C : N ratio
Vegetable market residues	26.32	1.32	0.41	0.61	19.94
Kitchen residues	26.87	1.78	0.58	0.83	15.10
Cow dung	36.10	1.23	0.76	0.82	29.40
Non-legume : legume vegetable crop residues (in 1 : 1 ratio)	26.67	1.94	0.63	0.71	13.75
Mixture of solanaceous, leguminous, cruciferous and cucurbitaceous vegetable crop residues (in 1 : 1 : 1 : 1 ratio)	29.93	1.75	0.61	0.93	17.10
Ipomea weeds	–	2.99	1.37	1.46%	–
Banana wastes	–	2.83	1.18	1.32%	–
Parthenium weeds	–	2.99	1.20	1.19%	–
Sugarcane trash	–	2.67	1.06%	–	–
Neem leaves	–	2.61	1.17%	–	–

*Compiled from various sources. –, Value is not reported.

Table 4. Mean nutrient content of some composted organic sources*

Organic source	Organic carbon (%)	Total nitrogen (%)	Phosphorus (%)	Potassium (%)	C/N ratio
Paddy straw-based poultry waste compost	23.05	1.89	1.83	1.34	12.20
Coir pith (in deep litter system)	30.03	2.13	2.40	2.03	14.1
Papermill compost	25.46	1.34	0.58	1.12	19.0
Press mud compost	33.17	3.1	1.95	3.5	10.7
Sugarcane trash compost	28.6	0.5	0.2	1.1	56.2
Seri waste compost	–	2.90	0.94	1.70	–
Castor cake compost	23.0	3.48	1.24	0.84	10.8
Bio compost	16.0	1.10	0.70	0.64	17.4
Vermicompost	23.1	1.59	1.63	1.07	15.7
Poultry waste compost using coir pith	30.0	2.13	2.40	2.03	14 : 1
Wheat straw compost	35.33	0.92	0.60	1.11	38.40
Mustard straw compost	33.59	1.04	0.54	1.35	33.59

*Compiled from various sources. –, Value is not reported.

products, tea, oil production, jute fibre, groundnut shell, wooden mill waste, coconut husk, cotton stalk, etc. Researchers have shown that by-products of sugarcane industries (bagasse and press mud) are a good source of plant nutrients, and may improve soil properties and yield of sugarcane[37]. Similarly, an increase in blackgram grain yield of 16% and 17% was observed in typic Haplustalf and typic Rhodustalf soil respectively, with the application of composted rice husk at the rate of 5 tonne ha^{-1} + 50% RDF + biofertilizers compared to 100% inorganic fertilization (RDF)[38]. Waste from other agro industries was also found quite effective in increasing the soil health and crop productivity[39]. Table 4 shows compost made from different agro industries waste and crop residues. The compost made from the agriculture waste was a good source of plant nutrients and organic matter (Table 4). The main constraints in the use of agro industries waste by the farmers are transportation cost and other environmental issues.

Biosolids (municipal solid waste)

Urban cities of India produce approximately 48 mt of municipal solid waste (MSW) annually[19]. The urban per capita solid waste generation ranges between 273 and 657 g/day/capita, and it is estimated that the amount of waste generated per capita per day is increasing at a rate of 1–1.5% annually in India. The cumulative land requirement for MSW disposal was 10 km^2 in 1997 and it would be 1400 km^2 by the year 2047 (ref. 40). In India, biosolids from different cities contain organic carbon in the range 25–39, total N 0.5–0.7%, P 0.5–0.8%, K 0.5–0.8% and C/N ratio 21–31. The nutrient composition of biosolids varied from site to site and according to the type of industries, city population, etc. It can be a promising soil-ameliorating supplement to increase plant productivity, reduce bioavailability of heavy metals and also lead to effective waste management[41–43]. Indoria *et al.*[44,45] found significant increase in the yield of some oilseed crops (*Brassica juncea*, *Brassica napus* and *Eruca sativa*) amended with sewage sludge (municipal biosolids) at the rate of 3% (on oven-dry basis) compared to control. They also reported higher accumulation of heavy metals (Cd and Ni) in different plant parts (stem, leaf and seed) in soils amended with biosolids (sewage sludge) compared to unamended soil. Mondal *et al.*[46] showed that application of MBS had positive effect on different soil parameters such as bulk density, which decreased by about 21% in the surface layer, increased the mean weight diameter (MWD), porosity, dehydrogenase activity and microbial biomass carbon. The main constraint in using biosolids in agriculture is that it contains different pollutants and harmful pathogens, which can deteriorate the soil and human health, once they enter into the food chain. Thus, there is an utmost need to treat them by suitable methods before application to crop land. Radiation-treated sewage sludge is a rich source of plant nutrients and organic matter; it does not carry any radioactivity and also kills harmful pathogens[47]. The transport cost and lack of the awareness among farmers towards use of biosolids are also important constraints.

Biochar

Biochars prepared from different feed materials and by different methods widely vary in their characteristics. Composition-wise, most of the biochars have a relatively small labile component (easily decomposable) compared to a much larger stable component (slowly decomposable). Studies pertaining to biochar use indicated that its application increased the availability of some nutrients like nitrogen, phosphorus, potassium and magnesium, and decreased Al toxicity by raising the pH of the soil[48,49]. Biochar displays important properties such as high surface area and cation exchange capacity, high carbon content, higher aggregate stability; it has a profound effect on soil properties and crop yield[50]. It has been reported that in North East India, weed biomass can be a potential source of biochar production, with a productivity of 20 tonne ha^{-1} annually. Moreover, the biochar produced from weed biomass of *Lantana camera* and *Chromolaena odorata* showed more or less similar characteristics with that produced from pine wood in portable metallic kiln process; hence this could be an effective means for biochar production in NE India[51]. Internationally, most biochar trials have been done on acidic soils. Studies have indicated that the effect of the biochar with respect to crop growth was more on acid soils compared to alkaline soils. Because adding biochar to alkaline soil caused further increase in pH, which had a detrimental effect on the yields, due to micronutrients deficiencies which occur at high pH. The energy required for the production and use of biochar was also taken into account in the light of its proven benefits. The knowledge gap and the availability of suitable technology for the conversion of biochar at individual farmer's end are the main constraints.

Coir pith

Coir pith is the by-product of coir industries, and it includes short fibres and dusts left behind after the industrially valuable long fibre of coir have been extracted from the coconut husk. It is estimated that about 7.5 mt of coir pith is produced annually in India (Table 2). The coir industry in Tamil Nadu alone produces nearly 4.5 lakh tonnes of coir pith every day, which requires safe disposal[52]. Research showed that coir pith compost added nutrients, enhanced soil microbial activity, reduced soil erosion, increased water holding capacity, and also enhanced the rainfed maize crop yield[23,53]. Rangaraj *et al.*[39] showed that addition of pressmud compost @ 12.5 tonne ha^{-1} and composted coir pith @ 12.5 tonne ha^{-1} favourably improved soil organic matter, pH, EC, microbial population and enhanced soil macro-(N, P, K) and micronutrients (zinc, copper, manganese and iron), and improved crop yield in finger millet. However, coir pith-decomposes very slowly in the soil because of chemical and structural complexity of lignin–cellulose complex with high content of lignin (30%) and cellulose (26%), and low pentosan–lignin ratio (>0.5)[53]. Kannan *et al.*[52] developed composting technique which they demonstrated to farmers at Ayalur Model Watershed, Erode district, Tamil Nadu. By this method coir-pith compost can be prepared within two months for use in agricultural lands.

Vermicompost

Vermicomposting is an effective process for efficient and quick recycling of organic waste to the soil; it is an eco-friendly process of converting organic waste into nutrient-rich product (Table 3). Moreover, raw materials for the preparation of vermicompost (crop residue, weeds, tree leaves biomass, cow dung, fruit and vegetable waste, kitchen waste, etc.) are easily available in different regions of India. Composition-wise, vermicompost contains a high level of plant growth hormones, enzymes and supplies and holds the nutrients for longer periods, improves soil microbial population and other soil properties[54]. In rice crop, yield increase of 17.17%, 30.29%, and 47.31% was noticed with the application of rice straw, sugarcane trash and water hyacinth vermicompost respectively, compared to application of 100% RDF (N, P, K)[55]. Application of vermicompost along with RDF and even sole application of vermicompost were found to enhance or maintain similar yield of fruit crops, pulses, cereals and vegetables[56,57]. However, sole application of vermicompost was found to reduce crop yield compared to chemical fertilizers during initial years; this might be due to less readily available nutrients in the initial years[58]. Therefore, it is always better to evaluate the beneficial effects of vermicompost in crop production in integration with chemical fertilizers and not alone. The major constraints in vermicompost production include: (i) lack of financial support for extending vermicompost units in a large scale, (ii) uncertainty in the demand, and (iii) absence of marketing channels.

Seri waste

Sericultural farm waste comprising silkworm litter, leftover leaves, soft twig and farm weeds from 1 ha area

Table 5. Biomass production and nutrient content of some green manuring crops*

Green manure crops	Crop age (days after sowing, DAS)	Dry matter (tonne ha^{-1})	N accumulated (kg ha^{-1})	P accumulated (kg ha^{-1})	K accumulated (kg ha^{-1})
Greengram (*Vigna radiata*)	55	1.76	25.62	9.46	21.64
Cowpea (*Vigna unguiculata)*	55	2.29	44.24	17.90	34.28
Sunnhemp (*Crotalaria juncea*)	55	2.27	50.43	11.08	40.23
Dhaincha (*Sesbania aculeata*)	56–59 at 50% flowering stage	18.0	Total NPK accumulated = 188.2 kg/ha		
Pillipesara (*Vigna trilobata*)	41–44 at 50% flowering stage	10.9	Total NPK accumulated = 111.0 kg/ha		
Guar (*Cyomopsis tetragonoloba*)	50	3.2	Total N accumulated = 91 kg ha^{-1}		
Sesbania rostrata	50	5.0	Total N accumulated = 95 kg ha^{-1}		

*Data have been compiled from various sources and the mean values presented.

can generate annually about 12–15 mt of waste. This waste has a tremendous manurial value of nitrogen (280–300 kg), phosphorus (90–100 kg) and potassium (150–200 kg) as well as micronutrients like iron, zinc, copper, etc.[59]. Gunathilagaraj and Ravignanam[25] have reported that the addition of sericulture waste substantially increases N, P, K, Mn, Zn and Fe content of the compost than farmyard manure (FYM) supplements. Application of compost manure produced using sericulture waste, including silkworm litter is highly beneficial for mulberry cultivation and is more effective than conventional FYM[60]. Kalaiyarasan *et al.*[61] reported that 50% seri waste + 50% RDF increased the grain and stover yield of hybrid maize compared to the 100% recommended dose of fertilizers. Moreover, in sericulture, cultivation of mulberry needs higher doses of chemicals and organics. Hence such nutrient-enriched material needs to be recycled back to the soil. An innovative farmer from Andhra Pradesh has produced annually 30 tonne of compost from 2 acres of mulberry cultivation field, as in general, each mulberry crop cycle (25–35 days) produces 2–3 tonne of mulberry biomass from a field of 2 acres[62]. The main constraint in this practice is the availability of suitable machinery for chopping the mulberry residues, and the lack of infrastructure and technology for good compost/vermicompost production.

Green manuring

In India, the area under green mauring crops is limited to 7 million ha (Table 2). The major green manuring crops include: *Sesbania aculeate*, *Sesbania rostrata*, *Crotalaria juncea*, *Tephrosia perpurea*, *Sesbania speciosa*, *Indigofera tinctoria, Vigna radiata*, *Vigna mungo* and *Vigna unguiculata*. Some tree species such as *Glyricidia maculeata*, *Pongamia glabra*, *Calatropis gigantecum*, *Azadirachta indica* and *Calotropis gigantca* are also used as green leaf manure. Green manuring crops are a good source of plant nutrients and organic matter. Table 5 provides information pertaining to the biomass and nutrient contents of some of green manuring crops. The biomass produced at different growth stages was significantly affected by seeding densities, nutrient levels and types of green manure crops. The results of the experiments conducted in sorghum using green manuring crop, viz. dolichos (*Lablab purpureus*) for four years (1998–2001) in Vertisols of Karnataka, India, indicated several benefits in terms of improvement in soil fertility, improved soil physical properties, organic C build-up and enhanced sorghum grain yield[63]. In another study, conjunctive use of 4 tonne ha^{-1} compost (prepared from farm-based organics) + 2 tonne ha^{-1} gliricidia lopping during sorghum crop growing season and 2 tonne compost and 1 tonne ha^{-1} gliricidia lopping application during mungbean crop season could save 50% of the N requirement of sorghum and mungbean respectively, besides improving the soil properties (pH, N, P, K, S, LC and MBC)[64]. Despite a high N_2-fixing potential, reduced nitrate (NO_3^-) leaching risk and lower fertilizer N requirements for succeeding crops, and positive effects on soil physical and chemical parameters and consequently crop yields, the area under green manuring crops has not expanded in India over the last few decades. Probably, land scarcity because of increasing demographic pressure, intensification in crop production and relatively low price of urea N are some of the main determining factors for the long-term reduction in green manure use. Unreliability of green manure performance, non-availability of seeds, and labour-intensive operations are other constraints in green manure use.

Tank silt

Desilting of ponds, water storage tanks or reservoirs was found to be an economically viable activity among farmers for creating more water storage capacity and returning the silt back to the fields as a source of organic matter and other plant nutrients. Sediment samples collected from 21 tanks in Medak district, Telangana were analysed and it was found that on an average, the samples contained 720 mg N and 320 mg P per kilogram of sediment. The organic carbon content of sediments varied from 5.3 to 27.2 g kg^{-1}, with a mean value of 10.7 g kg^{-1}. It has been reported that the application of 48,777 tonne of sediment to agricultural lands returned 520 tonne of carbon to the fields, thereby enhancing the nutrient availability for crop production. The tank silt samples also had higher counts of bacteria, actinomycetes and fungi[65]. Sharma *et al.*[66] reported (experiments conducted on ten farmers' fields in 1 ha land) that application of tank silt with improved management practices recorded an increase of 36.6% in maize grain yield over non-application of tank silt. Application of tank silt also benefited subsequent crop grown during *rabi* season and produced a significant residual response in maize–wheat, maize–mustard and maize–taramira cropping systems. Osman *et al.*[67] also reported 177%, 33%, 105% and 9% yield increase in castor, cotton, groundnut and mulberry respectively, with the application of tank silt compared to its non-application at different farmers' fields in Telangana. Desilting activity needs greater support from Government and non-governmental agencies to achieve multiple outputs like employment generation for the landless persons, rejuvenation of tanks and for enhanced productivity of dryland crops.

Role of alternative sources of organic amendments in climate change mitigation

It has been reported that estimated methane emission ranges from 0.33 to 1.80 Tg/yr, nitrous oxide 7 Gg/yr, and total carbon dioxide equivalent 38.2 Tg/yr from municipal solid waste of India[68,69]. It has also been estimated that burning of 98.4 mt crop residues emitted 8.57 mt of CO, 141.15 mt of CO_2, 0.037 mt of SO_x, 0.23 mt of NO_x, 0.12 mt of NH_3, 1.46 mt non-methane volatile organic compounds, 0.65 mt of non-methane hydrocarbons and 1.21 mt of particulate matter during 2008–09 (ref. 70). According to another study, 1 tonne of rice straw on burning releases about 3 kg particulate matter, 60 kg CO, 1460 kg CO_2, 199 kg ash and 2 kg SO_2 (ref. 71). As production of fertilizers for agriculture is itself an energy-intensive process, requiring large amounts of fossil fuel burning using the alternative sources of organic amendments, the demand for chemical fertilizer will decrease. In addition, greenhouse gas emissions could be reduced by substitution of fossil fuels for energy production by agricultural feed stocks (e.g. crop residues, dung and dedicated energy crops)[72]. It has also been reported that using crop residues, legumes, green manure, off-farm organic waste and improved soil and crop management practices help in C-sequestration by various ways[73]. It has been advocated that conversion of organic residues into a biochar could be a viable technology for long-term deposition of C and climate change mitigation strategy in different regions of India, because the average soil residence time for biochar can be up to thousands of years[49,74]. Thus, the use of the alternative sources of organic amendments in agriculture with appropriate management practices could be an effective strategy for mitigating climate change building robust soil health[75].

Future strategies

In order to effectively utilize the potentially available alternative sources of organic amendments in the country, the following strategies are suggested:

1. There should be rationalization in the use of alternative sources of organics in a way that crop residues are used as an animal feed, composting, mushroom cultivation, biochar production, source of energy, etc., based on their availability and composition.
2. There should be more research efforts for improving the efficiency of the alternative sources of organic amendments, such as practising good crop rotations and choosing the correct crop, proper method of conversion/preparation, proper mixing/application method in the soil, appropriate time of application, etc.
3. More research focus is needed to increase the efficiency and minimize loss of nutrients from different alternative sources of organic amendments using suitable additives/fillers/preservatives such as gypsum, rock phosphate, earth, lime, etc.
4. Some researchers have suggested that inoculation with Azotobacter, Azosperillium and phosphate-solublizing bacteria is helpful in obtaining good quality compost. More research is needed to improve the nutrient status of compost and to hasten the process of composting using suitable microbial inoculations. Transfer of recent scientific knowledge pertaining to advance composting methods, use of different microbes for decomposition, enrichment of compost and vermicompost through addition of micronutrients or bioinoculants, etc. should be promoted. Studies must focus on rapid decomposition of organic waste containing high cellulose, hemicellulose, polysaccharides and lignin content. For better decomposition of complex waste, microbial consortium containing a mixture of different decomposing soil organisms instead of a single strain needs to be promoted. It is important to emphasize here that composting and vemicomposting are the most simple and cost-effective technologies for treating organic fraction of municipal solid waste.
5. There is a need to explore the possibility of converting woody crop residues such as cotton stalks, pigeon-pea stalks, castor stalks and weeds crop residues into biochar on a large scale for field application. Dissemination of knowledge in this regard is important. Financial support to farmers to procure suitable kiln for biochar preparation will be highly encouraging.

6. Suitable machinery needs to be developed and made available to the farmers for shredding and cutting of crop residues for further recycling.
7. Sound strategy is required to educate farmers about the tremendous potential of alternative sources of organic amendments towards the overall soil health improvement, rather than supply of limited plant nutrients. In the past, most of the organic amendments have been projected and emphasized as a source of nutrients; the role played by the organic amendments in improving soil health should be readdressed and widely advocated.
8. Most of the sewage sludge plants are located in the big cities, resulting in high cost of transport to the farmers' fields. Hence, the Government must facilitate its transport and application by way of suitable incentives. Also, there is a need to create awareness among farmers to use the treated sewage sludge on their farms to improve soil health. Adoption of proper guidelines for municipal soil waste management and application to crop fields should be encouraged.
9. Crop residues are generally burnt after the harvest of the crops to keep the fields clean, as there is shortage of labour and also due to high cost of removing the residues. A sound strategy on account of technology and financial aspects is required for the efficient utilization of this valuable material.
10. Various crop management practices (viz. residue retention, cover crops, and inter-cropping with legumes, tree-based green leaf manuring, appropriate crop production systems/cropping systems, use of biofertilizers, integrated nutrients management, etc.) have been proved effective in improving organic matter in the soil and consequently soil health and crop yield on a sustainable basis[76–78]. Indoria *et al.*[79] have made an extensive review on the impact of conservation agriculture on soil health and concluded that conservation agriculture substantially improves soil health. In order to popularize the above-mentioned alternative farming practices among farmers through agricultural extension system, sound policy needs to be developed.

Conclusion

It has been proved that without regular application of organic amendments and recycling of available organic residues, we cannot maintain soil health and sustain productivity and ensure high responses to added fertilizers. Moreover, over dependence only on chemical fertilizers is posing serious threat to ecological balance. The enormous amount of alternative sources of organic amendments available in the country for recycling and bio-conversion should be explored to utilize their embedded nutrients and organic matter for sustainable soil health and crop growth. This will not only help meet the deficit of fertilizer nutrients, but also to conserve energy, minimize pollution, save foreign exchange and improve the fertilizer use efficiency. Recent scientific advancements need to be exploited for more effective, economical and sustainable recycling of these alternative sources of organic amendments. Most importantly, as some of the studies have also revealed, sole application of organic amendments cannot meet the nutrient requirements of the crops; hence they should be used in conjunction with inorganic fertilizers for maintaining the desired crop productivity. In order to encourage the use of alternative sources of organic amendments in agriculture on a large scale, we need to work at four levels, i.e. (i) focused research for safe handling of the alternative sources of organics using the state-of-the-art technology, (ii) improving awareness among farmers, and rural and urban communities about the importance and potential of these organic amendments in improving soil health and crop productivity, (iii) training and skill improvement of the communities in effective handling of the alternative sources of organic amendments, and (iv) development of appropriate policies and bye-laws for onsite safe processing of the alternative sources of organics by the industries, and suitable incentives for encouraging the farmers to use them on a larger scale.

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