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Review

Sustainable agriculture options for production, greenhouse gasses and pollution alleviation, and nutrient recycling in emerging and transitional nations - An overview

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ABSTRACT

Previous and current agricultural practices have contributed to environmental pollution, which is further affecting food security, human health, and climate. Yet, agriculture cannot be eliminated, because, of its promising role in ending hunger, reducing poverty, improving nutrition, and achieving food security in low-middle income countries. Hence, there is a need for shift from 'unclean' practices to sustainable practices. Similarly, differences in pollution, among nations call for regional changes or intervention in agri-food practices to reduce global pollution. These practices are essential for African and Asian countries. Of the many methods proposed in this review, localized technology improvement and globalized sustainable intensification are of high impact models having the potential of mitigating greenhouse gases up to an extent of 30%. Various methods of achieving these measures include, but not limited to, the shift in management systems of crop and livestock production, encouraging agriculture and veterinary practices with less environmental impact and high adaptation, enabling nutrient recycling or recovery, resource-use efficiency, mitigation of nitrous oxide and methane from soil, implementation of integrated farming system and insect farming. Government agencies along with agri-food producers, processors, and farmers must be ready to change their current agricultural practices by adopting new methods. The review conclude that the sustainable agricultural production is possible through the use of low-priced local resources that are capable of increasing soil carbon storage, thus combating the pollution in countries with a transition economy.

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1. Introduction

Agriculture is the world's most significant driver of environmental change (Godfray and Garnett, 2014) and is vulnerable to the climate changes, which are often related to diverse emissions and run-offs of pollutants to land, water, and atmosphere. Agriculture, contributes to greenhouse effect (by emission of methane (CH_4) carbon di-oxide (CO_2), and nitrous oxide (N_2O)), eutrophication phenomenon (by nitrogen and phosphorus run-off), pollution of waterbodies (through leaching and erosion), global phosphorous or nitrogen pollution, climate change, air pollution, and stratospheric ozone depletion. Global agriculture is being affected by climate-related disasters such as drought and flood, which are further triggered by agricultural pollution. Despite the environment-related adverse effects, agricultural production practices are the primary routes to achieve food security and end the world hunger by improving the protein and other nutrients in the diet of food-insecure people. Apart from reducing poverty through increased income, sustainable agriculture can provide clean energy and water in low- and middle-income countries. Therefore, smallholders, commercial farmers, and food processors in the world must practice sustainable agri-food activities to ensure a food secured systems at the local, national, or regional level. FAO (2003) defined food security as when there is physical and economic access to sufficient, safe and nutritious food. Sustainable agriculture should provide nutritious food sufficiently for all while lessening environmental risk and allowing food producers to earn decent income (Eyhorn et al., 2019). Alteration in current untenable agricultural practices into sustainable procedures could contribute to food security apart from mitigating the climate change. The aforementioned procedures necessitate the need to improve production practices and overall efficiency of resources used in the agri-food industry.

The current business-as-usual approaches such as food wastage, continuous fertilizer application, pollution of surface and underground water, air pollution, and increased greenhouse gas (GHG) emissions, are unsustainable agricultural production practices. Under a business-as-usual scenario, GHG emission is estimated to grow by 37%, 32% and 21% in Asia, Africa, and Latin America, respectively, by 2050, most of which have developing and transitional nations (Frank et al., 2019). Managing animal and aquaculture diets to avoid over-feeding of nutrients and unnecessary enrichment of manures with feed N and P is important on a small- and large-scale. The livestock sector is responsible for emitting 14.5% of all anthropogenic GHG. Data showed that out of total anthropogenic GHG (49 Gt CO_2 eq/year), livestock accounts for the 7.1 Gt CO_2eq/year. Of this, 3.1 Gt CO_2eq/year is in the form of CH_4, 1.92% Gt CO_2eq/year as CO_2, and 2.06 Gt CO_2 eq/year as N_2O (Gerber et al., 2013). Among the 18 Tg N emitted annually, 45% is contributed by anthropogenic sources while agriculture alone accounts for 60% of these sources (Syakila and Kroeze, 2011). Meanwhile, an average of more than 80% and 25–75% of N and P consumed, respectively, are lost to the environment (Sutton et al., 2013). The need to improve sustainable agricultural practices through higher nutrient use efficiency, increased nutrient recycling, reduced food waste, enhanced food production, reduced GHG emissions, and improved agricultural productivity, has become an area of significant interest and led to multi-disciplinary research among scientists. Therefore, this review is meant to provide an overview of applicable changes that are needed to ensure sustainable agricultural production.

2. Environmental pollution by agricultural practices

2.1. Overview of global agricultural pollution

The impact of agricultural practices on the environment is of much interest because of the negative effect of nutrient run-offs of farmlands, which harbor several agricultural or livestock operations (Vallejo-Hernández et al., 2019). Furthermore, between 2001 and 2010, agriculture in Asia, America, Africa, Europe, and Oceania contributed 44%, 25%, 15%, 12%, and 4% of global GHG emission, respectively (FAO, 2014a). In Africa, enteric fermentation, manure left on the field, synthetic fertilizer, and manure management accounted for 38%, 27%, 3%, and 2% emission in agriculture, respectively, for 2001–2010 (FAO, 2014a). In the same period, enteric fermentation, manure left on the field, synthetic fertilizer, manure management and crop residue accounted for 33%, 18%, 11%, 7%, and 4% of emission from agriculture in Asia (FAO, 2014b). Methane emission from agriculture accounted for over 40% of global emission (FAO, 2013). Methane is mostly generated from ruminants during enteric fermentation (a biological process for removing CO_2 and hydrogen from the rumen to maintain fermentation) or anaerobic decomposition of the excreted manure. Overall, the comparison of the data from 1961 to 2012 revealed a total increase of 243% and 144% of GHG emission from Africa and Asia, respectively (FAO, 2014a, b). These emissions have metabolic and polluting implication for both animal and the environment.

2.2. *Nitrogen and phosphorous pollution*

Agriculture-based environmental pollution occurs where there is high manure production - usually due to high livestock population or intensification. Besides, the oversupply of inorganic fertilizers is a common cause of pollution in countries with heavily subsidised fertilizer (Sutton et al., 2013). The collected facts and statistics together provide a vast range of nutrient wastage that pollutes the environment. For instance, out of 180 Tg N inputted into world nitrogen cycle yearly, about 82% of the nitrogen is consumed by livestock through crop and grass production while only 18% is available for direct human consumption (Sutton et al., 2013). This indicates poor nutrient use efficiency of nitrogen and phosphorus in the agricultural production systems. Phosphorus pollution occurs through excessive application of systhetic fertilisers, leading to undue loading of water bodies with run-offs from agriculture fields. Another important contributor to phosphorus pollution are animals reared in intensive system which are often overfed. The flowcharts of nitrogen and phosphorus pollution with relation to agriculture and allied sectors are presented in Figs. 1 and 2, respectively. The excess amounts of N and P in manure should be recovered prior to application in fields. Compaction, composting, anaerobic digestion, solid-liquid separation, chemical amendments, thermochemical conversion, nitrification-denitrification, and deammonification are the important methods of N recovery from animal waste. Chemical precipitation and wet extraction are the two most essential methods for P extraction from manure. The concatenation of above-mentioned techniques in manure management systems could aid in sustainable nutrient recycling systems (Szogi et al., 2015). Apart from these methods, direct feed manipulation decreases the total N and P excreted into the environment, thus abating the acceleration of eutrophication phenomenon in lakes and rivers (Reddy et al., 2019).

Phosphorus (P) is an important nutrient in livestock and crop production systems and humans. In livestock, high quality diet fed livestock are known to produce fecal and urine output rich in nutrients, which leads to low nutrient use efficiency and environmental pollution. More than 90% of the global phosphorus mined is used in production of food and feed (Prud'homme, 2010). The nonrenewability of phosphorous mined from phosphate rock is a cause for concern on sustainability of the practice. This has increased concern on future fertilizer availability and calls for better nutrient management including the comprehensive recycling of human waste due to nutrient embedded in it (McConville et al., 2015). Human waste contributes to environmental pollution due to sewage system leakage into the river. Annually, human excretes 3 to 5 Tg of P, among which 3 Tg reaches the river through sewage system (Van Vuuren et al., 2010). It is estimated that annual global N and P emissions from sewage are expected to increase by 87.5–150% and 85–139.5% respectively in 2050 from 6.4 to 1.3 Tg of N and P in 2000 (Van Drecht et al., 2009). Therefore, recycling of human faeces as fertilizer could help to reduce phosphorus pollution in water bodies. Decomposition of the human fecal material is the standard principle in recycling the recalcitrant pollutants. Decomposition can be done by biological, thermal, mechanical, chemical, and thermochemical methods. The biological treatment of human faeces through activated sludge process has been shown to remove the phosphorus more efficiently compared to other treatments (Harder et al., 2019). Acid leaching is another potential strategy in separating fecal-derived organic matter and heavy metal, especially phosphorus separately (Jadhav et al., 2017). Further, the sorbents such as charcoal and calcined struvite are known to extract several macronutrients such as nitrogen, phosphorus, and potassium from liquid streams (Nakhli et al., 2017). The separation of phosphorus from fecal ashes or slags are well described in detail by Viskari et al. (2018).

In addition, biocharing of animal and human fecal wastes could help to reduce P pollution. Broiler manure are the richest in nutrients compared to different livestock manures and their manure are having proportion of P (N:P:K–6:2:3) (Chritensen and Sommer, 2013). Due to the environmental footprint of phosphorus excretion and accumulation in livestock farms; phytase have been used to reduce its losses from livestock operations and the manure used to generate biogas (Vallejo-Hernández et al., 2019). In addition to biogas, bio charing of broiler manure increased the sodium bicarbonate extractible phosphorus - labile P in the broiler manure (Keskinen et al., 2019). Similarly, human manure is rich in P, instead of wastage it could also be converted to biochar, and this will concentrate its P content. Therefore, biochar of animal and human wastes could increase P availability and reduce its run-offs and leakage into waterbodies from agricultural production and sewage system respectively.

2.3. *Brief implication of pollution*

Nitrogen (in the forms of NH_3, NOx, NO_3-, N_2O, and organic nitrogen) and phosphorus pollution occur from large number of sources, such as animal wastes, synthetic fertilizer, losses from soil during application of manure onto the field, and emission from human excreta (Aneja et al., 2012). Leaching of excess N and P causes air, soil, and groundwater pollution and contributes to eutrophication phenomenon, which affects aquatic life diversity. Furthermore, excess nitrogen losses to atmosphere causes the formation of several aerosol compounds of fine particulate matter, thereby affecting human health by reduced visibility (Erisman et al., 2011; Lelieveld et al., 2015). Nitrous oxide and particulate matter and other air pollutants are associated with tearing and ocular irritation of the eyes, conjunctivitis, incidence of diabetes, Crohn's disease, and ageing of the brain (Schraufnagel et al., 2019).

The nitrogen entered into the environment may convert into different forms and result in a process referred as nitrogen cascade, which creates a wide range of environmental impacts. For instance, the reactive nitrogen may convert into ammonia, nitrate, nitrogen oxide, nitrogen dioxide, nitric acid, organic nitrogen, thereby causing social, health, and environmental impacts. In additon to the environmental effects, the cost of nitrogen pollution is another important parameter which has to be considered, while estimating

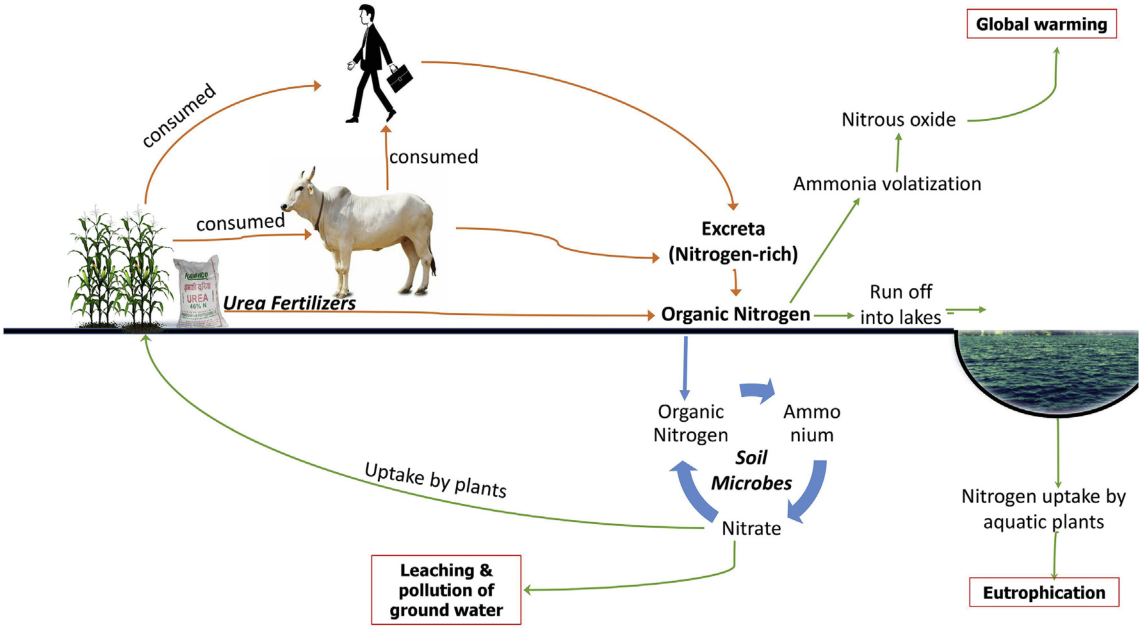


Fig. 1. The flowchart of nitrogen pollution with relation to agriculture and allied sectors.

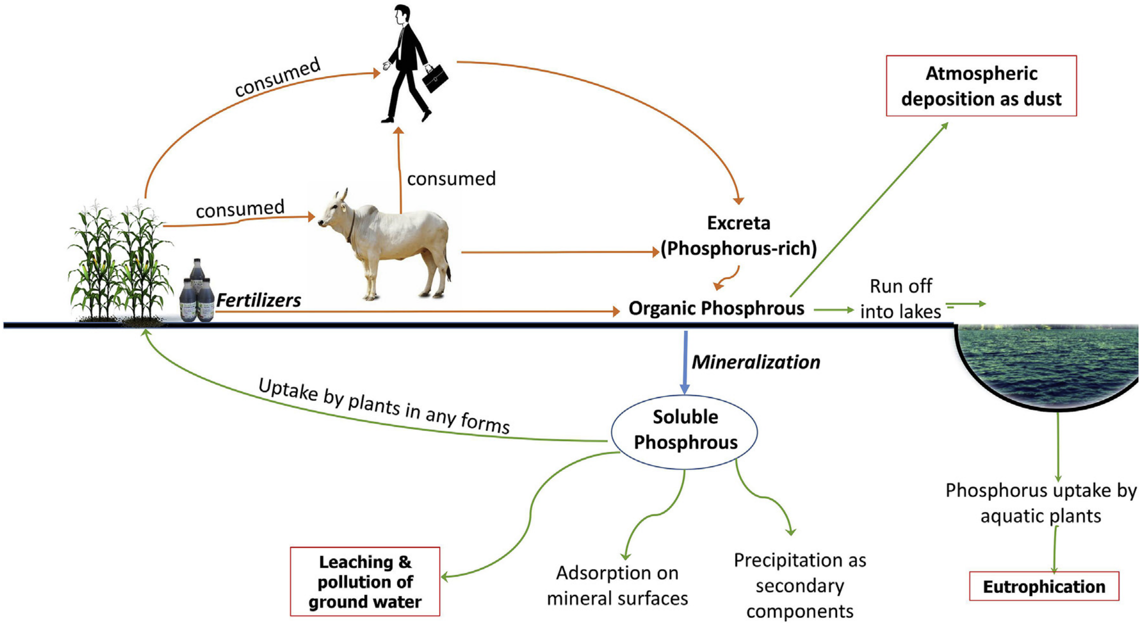
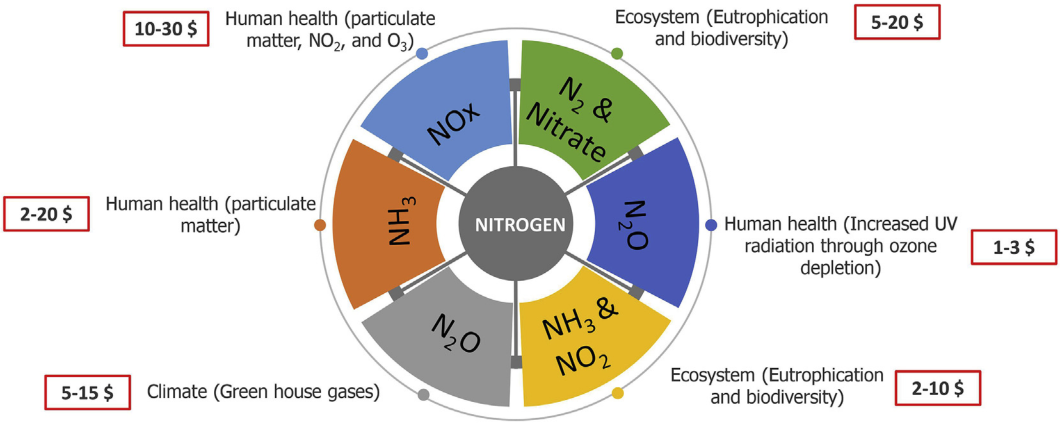


Fig. 2. The flowchart of phosphorus pollution with relation to agriculture and allied sectors.

the implications of nitrogen-based pollution. An innovative study by Brink et al. (2011) determined the cost of nitrogen pollution by considering the impacts of climate, ecosystems, and human health of various N-based emissions. In the present review, these results were compiled and provided for the readers in pictorial form (Fig. 3). Further, the mitigation of eutrophication phenomenon caused by phosphorus loads is known to associate with costs at significant level. Fig. 4 summarizes the costs of various mitigation measures as affected by different aeration systems used to decrease the phosphorus loads from lakes. The figure was prepared by obtaining the data from ENSR commission (2004), BRP commission (2004), and Chandler (2013).

3. Proposed solutions

The effects of GHG emission on biophysical resources call for reduction of pollution directly and indirectly from agricultural sources and other sources involved in agricultural processes respectively. Nutrient concentration is usually associated with the economic strength, subsidies, and priorities of nations. Some nations are challenged by nutrient deficiency - which affects their food productivity, whereas other countries deal with continuous nutrient usage, thus causing pollution (Sutton et al., 2013). Nutrient deficiency is common in many developing nations in sub-Saharan Africa, Southeast Asia, and South Asia. Excessive nutrient losses



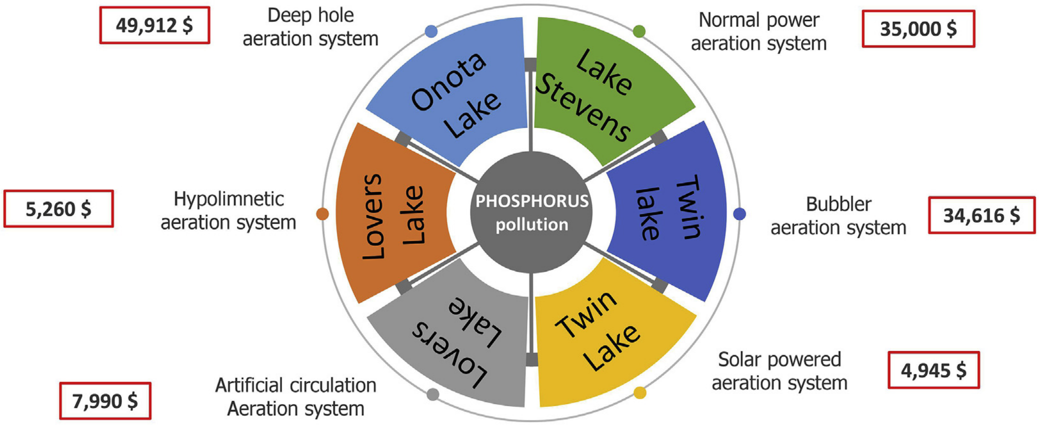
* NO_X, NH_3, N_2O, and N_2 – Emitted nitrogen forms
* Human health, climate, or ecosystem – Effects by various forms of nitrogen
* Peripheral red boxes - Estimated cost ($) per kg nitrogen emitted

Fig. 3. Costs associated with nitrogen pollution.

occur in America and Europe, while the intermediate is common in industrialized Asia. These variations indicate that regions contribute to environmental pollution in different capacities and therefore no one-size-fits-all solution, rather, solutions will differ from place to place.

3.1. Adoptable proffered solutions

Animal feed supplementation and anaerobic digestion (biogas) could help to reduce GHG emission and recycle nutrients, thereby increasing the nutrient use efficiency. These strategies are more beneficial in the nations and regions such as China, India, Africa, and Latin America that produce beef and milk under higher emission intensity (Frank et al., 2019). Sutton et al. (2011) report that ruminants (cattle and sheep) have lower nutrient (N and P) use efficiency compared to pigs and poultry. This imply that the nutrient use efficiency of the non-ruminants is superior to ruminants. Inferior quality and substandard composition of diet offered to ruminant species might be one of the reasons for inefficient nutrient usage. Besides, most of the ruminant breeds in developing nations are of low productive potential compared to monogastric breeds, which are usually fed with balanced diets. Mostly, the ruminants in developing countries are raised for meat production, which is often associated with low feed efficiency and high emission intensity (Herrero et al., 2013) due to slow growth rate. Further, this affects the efficiency of nutrient input in meat production compared to milk, which has associated benefits such as carcass value and newborn for replacement. Shifting from the intensive or higher stocking of ruminants to monogastric (poultry, rabbit, swine, and horses) farming is a promising alternative in using nutrients more efficiently. This is because monogastric products (meat and egg) have lower emission intensities than



* Onota, Lovers, Twin, Steven lakes – Selected lake for the study.
* Deep hole, hypolimnetic, A.circulation, Solar powered, Bubbler and Power – Different types of aeration systems employed for removal of phosphorus
* Peripheral red boxes – Annual operation and management cost ($) of aerations systems.

Fig. 4. Costs associated with phosphorus pollution.

ruminant-based commodities (milk and meat). According to Herrero et al. (2013), the GHG emission from monogastric species is only 10% of total livestock emission. They also reported that the global warming potential of one kg edible poultry protein is 549% lower to that of pork-derived protein. This indicates monogastric specie differences in nutrient use efficiency and environmental pollution - implying that poultry are nutrient use efficient and ecofriendly compared to swine in their product output.

Apart from reducing the consumption of animal products, the nitrogen usage efficiency in agriculture and livestock systems should be improved to prevent the release of reactive nitrogen at higher levels (Bodirsky et al., 2014). In regions with too little nutrient problem in their soil, the reactive nitrogen and phosphorus pollution could be reduced by improving the water quality and fertilizer value equivalence of animal manure (Sutton et al., 2013). These approaches will integrate pollution mitigation with food security and energy generation. Recently, Du et al. (2018) proposed that globalized ruminant expansion, globalized feed expansion, localized technology improvement, and globalized sustainable intensification could reduce the emission from agriculture. The globalized ruminant expansion involves importing ruminant products from nations with lower emissions intensities production system. Furthermore, the green source trading or global feed expansion involves importing additional supply of livestock feed from international markets with low emissions production systems. Localized technology (green technology) may vary but it seeks to combine green source trading and application of global techniques that reduces emission. This localized technology must be tailored to suit the needs and financial capacity of each region, hence the variation. Adopting the combination of green technology with green-source trading could contribute to the sustainable intensification of agriculture.

Frank et al. (2019) suggested a shift in management systems of crop and livestock production. This shift in management practice may integrate various production systems such as feed crop cultivation, feed processing, livestock rearing, raw product processing, wastewater remediation, manure treatment, and biogas fermentation. As such, countries in regions with risk of food insecurity, could plant some neglected crops such as pearl millet, finger millet, fonio (acha) and sorghum. These crops are drought resistant, and few of them are even rich in amino acids such as methionine, lysine and cysteine, which are generally deficient in cereals. For instance, pearl millet is highly tolerant of drought and can support good yield in too arid and hot zones (NRC, 1996). These crops are often the only crops adapted to dry climate and erratic rainfalls; for instance, millets need 3.5 times less water than rice to grow (ICRISAT, 2000). Millets are said to be nutritious, gluten-free, and rich in protein, iron, and zinc. Most of the millets are tasty with many diverse food products derivable from it. The rich iron content could help to reduce anaemia in children and pregnant women. Furthermore, the millets are known to have less water footprint and are nutritious compared to rice, which is a common staple food.

3.2. Potential benefit of solutions

Localized technology improvement strategy has potential to dramatically reduce global GHG by 31% (122 Tg CO_2-eq) and NH_3 by 39% (1.1 Tg) (Du et al., 2018). The globalized sustainable intensification option led to a declined global GHG emissions by 32% (129 Tg CO_2-eq) and NH_3 by 41% (1.12 Tg) (Du et al., 2018). Green sourcing has the potential to decrease transferred GHG and NH_3 by 78% (83 Tg CO_2-eq) and 92% (0.6 Tg), respectively (Du et al., 2018). From these scenarios, localized technology development has an effective regional mitigating potential, which if applied, will have a global impact in reducing environmental pollution. Combining sustainable intensification (localized technology) with importation of livestock feed from countries tenaciously following low emission-based production systems would reduce global and transferred GHG emission. In this regard, the carbon pricing system scenario proposed by Frank et al. (2019) is expected to create interest in mitigation emission from ruminant products (i.e., meat and milk) and in crops (rice and cereal) in China, India, sub-Saharan Africa, and Latin America. According to the system proposed, the carbon output is priced as low (US$20/t$CO_2$eq), medium (US$100/tCO_2eq), and high (US$950/t$CO_2$eq) ranges. We opine that, if the pricing system is implemented, farmers in low- and middle-income countries would benefit economically, as well as, increase practicing of low emission agri-food practices.

4. Strategies to reduce environmental pollution of agricultural practices

Although several suggestions exist toward reducing ruminant population because of their contribution to GHG, an investigation in India revealed a little to no growth in CH_4 emission between 2010 and 2015 (Ganesan et al., 2017). Therefore, curbing the livestock rearing as a means of reducing GHG may not be acceptable in developing or emerging nations where livestock contributes to their livelihood. Sustainable livestock production helps in reducing the deposition of agro-industrial waste in the environment and improving the valuable benefits obtained from livestock (income, employment, and raw material). Similarly, livestock rearing in developing countries could be an eco-friendly practice, because of the valorization of human inedible agriculture waste. Sustainable development of livestock has the potential to enhance the livelihood of 18% of the world population that depends on livestock for living (FAO, 2016). The emission intensity of livestock, especially from ruminants in developing nations is very high, and reducing it needs increased output of animal product per unit of feed offered. Regions, with high emission intensity especially those associated with low feed efficiency, due to poor quality feed, and low animal productive potential, has high potential for reducing emission and improving feed efficiency by shifting management practices to well-proven and adaptable ones with less emission. Improvement in ruminant management practices, to produce less emission per kilogram of product and with less water footprint (i.e., more product per unit of water consumed), will be a sustainable practice (Table 1). Therefore, if developing nations are aiming to reduce emission without reducing ruminant population, improvement in yield derived from farm animals is essential. Similarly, application of local technologies, recycling of nutrients, and improvement in agriculture practices could help to reduce agricultural pollution and improve productivity (Fig. 5).

4.1. Animal feed supplementation

Enteric CH_4 emission accounts for the highest agricultural GHG emission in Asia and Africa from 2001 to 2010 (FAO, 2014a). In Africa, CH_4 is expected to increase from 7.8 million tons in 2000 to about 11.1 million tonnes by 2030 (Herrero et al., 2008). According to a recent study, the growth rate of CH_4 in atmosphere, especially in the tropics and subtropics was tremendously increased in 3 years period i.e., 2014 to 2017 (Nisbet et al., 2019). This CH_4 production in livestock deprives about 39.5 KJ energy for each liter of enteric CH_4 emission (Guan et al., 2006). Reducing emissions without lessening the ruminant population requires either good quality feed supplementation or improved yield. Therefore, increasing ruminant productivity while decreasing emission is an area of nutritional interest. Because of the diverse mechanism of actions, several feed supplements are being considered as an effective measure to abate

Table 1
Benefit of the options for sustainable Agriculture.

Challenges	Option	Effect/Advantage
Ruminant greenhouse gas emissions	Plant rich in saponin and tannin	10–49% decrease in methane emission
	Aspergillus terreus produces lovastatin	Decrease in methanogen, reduction in methane output
	Algae growth and supplementation (*Asparagopsis taxiformis, Dictyota bartayresii, Cladophora patentiramea)*	Water remediation, biofertilizer, biogas and 30–99% decrease in methane production
	Feedlot system with 100% Leuceana feeding	16–57% decrease in greenhouse gas emissions intensity
	Separate feeding of roughages and concentrate to ruminant	13.43–14.66% decrease in methane
Environmental pollution of manure and agro industrial waste	Conversion of manure in anerobic digester	Bioenergy for cooking and electricity, biodigester effluent as biofertilizer because it contains Nitrogen and Phosphorous,
	Biocharring of manure and agroindustry waste	Carbon sequestration, improve crop yield, reduces NH_3 emissions, reduced cumulative N_2O loss, CH_4 emissions, CO_2 emissions by 44–134% when added to slurry
	Recycling of plant residue, fruit and vegetable waste for ruminant	Reduced urinary nitrogen losses and nutrient recovery
	Application of farmyard manure instread of slurry	36% and 41% reduced overall net greenhouse gas emissions emissions and intensity respectively
	Insect farming	Can be grown on manure and agricultural by-product, could be used as feed ingredient, less environmental impact compared to other edible protein sources, insect-derived products are great potential as immunostimulant and modulator of the animal microbiota.
Agriculturla waste water	Microalgae (*Chlorella* sp, *Gracilaria birdiae*) and water hyacinth growth	28–94% nitrogen and phosphorus recovery, and decreased N_2O emission. water hyacinth may be used as biogas digestion, could be used for cooking instead of wood, and as biofertilizer
	Application of carbon fiber in wastewater treatment plant	85% decrease in N_2O emission
Adaptation to climate change	Increase in Small ruminant instead of cattle	Lower emission intensity per kg product
	Genetic improvement of indigenous livestock with disease and heat tolerant breed	Improved product output, easy adaptation to environment
	Research and development, genetic improvement and cultivation Pearl Millet, Finger millet Sorghum and African rice (*Oryza glaberrima)*	requires less water, rich in protein, higher resistance to diseases and pests, tolerates fluctuations in water depth, and can grow in severe climates.

enteric methane emission. Fig. 6 shows the dietary strategies and mechanism of mitigation activities and was compiled from the literature by Hook et al. (2010). Readers are strongly recommended to refer the two recent reviews by Islam and Lee (2019) and Haque (2018), which dealt on feeding various feed additives with anti-methanogenic potentiality.

4.1.1. *Phytogenic intervention*

Plants rich in tannin and saponin could be used in supplementing the diet of grazing animals to reduce GHG emission. Several tannin and saponin rich plants such as *Delonix regia, Mangosteen peel, Acacia mearnsii, Enterolobium cyclocarpum, and Musa paradisiac* hay have been observed to increase nitrogen retention and reduce CH_4 emission in a range of 10–49% (Polyorach et al., 2016, Alves et al., 2017; Albores-Moreno et al., 2017; Freitas et al., 2017; Supapong et al., 2017). Diet consumed by animals influences the nutrient excreted as nitrogen, phosphorus, or enteric CH_4 emission. The normal range of N_2O emissions (0.3–0.5 g/cow per day) may vary depending on the dietary condition (Rotz and Thoma, 2017). Ensiling forages adds excess emission from the silos, which is often also related to silo-fillers disease (Wang and Burris, 1960; Gerlach et al., 2018). The feeding of corn silage and grass hay instead of alfalfa silage could help to reduce GHG emission from cattle. Measuring N_2O production through the closed lid of rumen-cannula resulted in 0.246, 0.857, and 0.171 ppm N_2O production in steers fed corn silage, alfalfa silage, and grass hay, respectively (Gerlach et al., 2018). The same study revealed that corn silage and grass hay produced lower N_2O emission by about 248% and 400% compared to alfalfa silage when fed to cattle. Methane was also lower in corn silage fed steer by 22%. Higher N_2O production from fermented alfalfa silage may be related to its higher crude protein or nitrate content (Gerlach et al., 2018). Therefore, chemical composition should be considered when choosing plant to use for silage or forage to feed to animals.

4.1.2. *Fungal intervention*

Incubating fodder with fungi, fungal enzymes, and their metabolites could help improve feed quality and reduce GHG emission. Based on several works of literature, fungi such as *Pleurotus ostreatus, Trametes versicolor, Aspergillus awomori*, and *Aspergillus terreus* have been used in animal nutrition. Fermentation with *Aspergillus terreus* resulted in secondary product known as lovastatin, which was well known to possess antimethanogenic ability by reducing the growth and activity of pure methanogenic bacteria (Wolin and Miller, 2005). In Asian countries, rice and wheat are the major cereal resources, whose straw is usually burnt, thus causing GHG emission at enormous levels. *Aspergillus terreus* can be used to reduce lignocelluloses content in straw and methanogenic activity in rumen through the production of lovastatin. In a recent study, Azlan et al. (2018) found that fermentation of rice straw with *Aspergillus terreus* produced lovastatin at 131.4 mg/animal/day. In the same study, the authors revealed an increased rumen bacteria population by 123% and reduced total methanogens and CH_4 production by 24% and 32–42%, respectively. Because of the increased oil palm cultivation in the tropics, palm kernel cake, an agro-industrial byproduct is extensively available as a feed ingredient. Candyrine et al. (2018) fermented palm kernel cake with *Aspergillus terreus*, which produced an average of 850 mg lovastatin/kg dry matter. Further, the supplementation of lovastatin at 2, 4, and 6 mg/kg BW/day reduced the CH_4 emission by 11.4%, 21%, and 21%, respectively, without affecting VFA negatively. The anti-methanogenic potentiality of lovastatin is attributed to its inhibitory activity of HMG-CoA reductase in the microbes' cell membrane biosynthesis (Wang et al., 2016).

4.1.3. *Algae*

Algae are photosynthetic organisms that can grow in polluted freshwater and marine environment. Seaweeds, also known as microalgae, are fast-growing organisms and can be used in bio-based fertilizer preparation (Safinaz and Ragaa, 2013), biogas

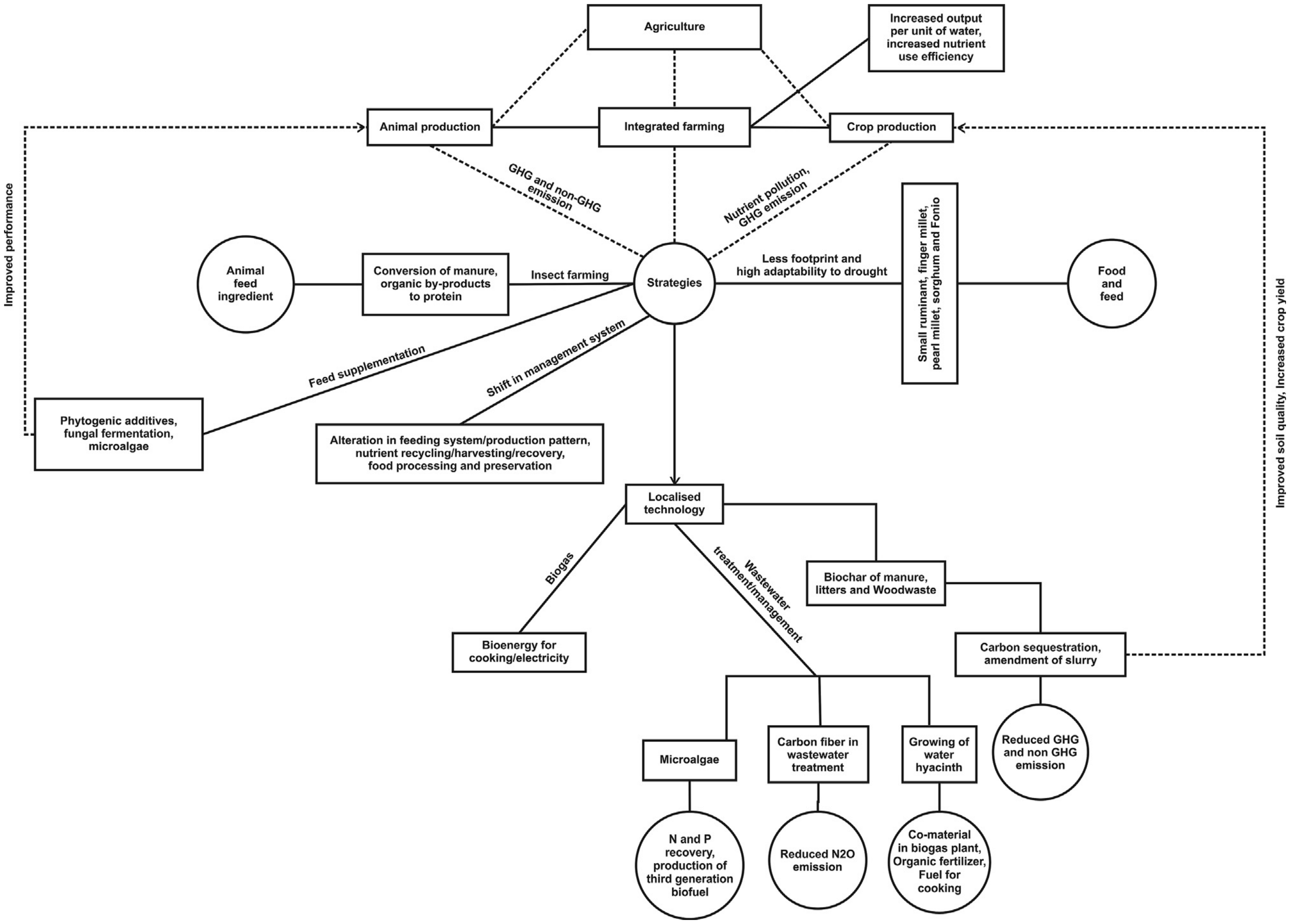


Fig. 5. Strategies for sustainable agricultural production.

production (Nkemka and Murto, 2010), bioremediation, and wastewater treatment (Kim et al., 2017). Incubation of red algae (*Asparagopsis taxiformis*), brown algae (*Dictyota bartayresii*), marine green algae (*Cladophora patentiramea*), and freshwater algae (Oedogonium) reported a reduction of CH_4 emission by 92.2%, 98.9%, 66.29%, and 30.3%, respectively (Machado et al., 2014). Asparagopsis and Dictyota have been reported to have strong antimicrobial properties due to the higher quantities of secondary metabolites (Paul et al., 2006). Dictyota is particularly rich in terpenes (Blunt et al., 2013) while Asparagopsis contains bromine and chlorine haloforms (Moore, 1977; Paul et al., 2006). The anti-methanogenic potentiality of terpenes and haloforms is well evident (Genovese et al., 2009). In another work, the incubation of green macro-algae (Ulva sp.), brown macro-algae (*Laminaria ochroleuca*; *Saccharina latissimi*), and red macro-algae (Gigartina sp., *Gracilaria vermiculophylla*) in rumen liquor strongly reduced methane emission without any detrimental effects on *in vitro* fermentation (Maia et al., 2016). The antimethanogenic potentiality of these seaweeds could be connected to the presence of organo-bromic compounds such as bromomethane and bromoform (Patra et al., 2017). Further, a recent batch-fermentation study revealed that the supplementation of red macro-algae (*Asparagopsis taxiformis*) at 5% level to Rhodes grass reduced the CH_4 production by as high as 95%, promoting its use as biotic CH_4 mitigation strategy (Roque et al., 2019).

Therefore, macro algae have the potential to reduce CH_4 production; however, most of the algae-based research was conducted *in vitro* and hence needed further investigation *in vivo* to determine their efficacy. Nevertheless, it is noteworthy that excessive harvesting of seaweeds from oceans may disturb the ecological balance and inturn contributes to more pollution. Hence, the seaweeds have to be cultivated on large scale as a feed for the ruminants, instead of harvesting from natural water bodies.

4.2. *Adoption of localized technologies*

The current African population is expected to double by 2050, and the continental gross domestic products will increased by three-fold from its current state, as well as, the purchasing power of consumers (WDI, 2018; UN, 2018). This phenomenon increases the demand for crop and animal protein, consequently pressurising on energy and power supply and increased environmental pollution from livestock and other agriculture sectors. Increase in livestock results in increased manure and wastewater, which will cause environmental pollution if not managed properly. Therefore, there is a need for advancement of local or adapted technology in using the agriculture and livestock waste to provide eco-friendly, healthy, and affordable food to food-insecure regions. Application of local technology like biogas and biochar could be affordable sustainable options.

4.2.1. *Biogas*

Microbial energy conversion processes (biogas systems) offers a promising and effective approach for organic wastes recovery. It is a method suited for biological degradation of waste and generation of renewable bioenergy (Beurskens et al., 2011). Biogas production

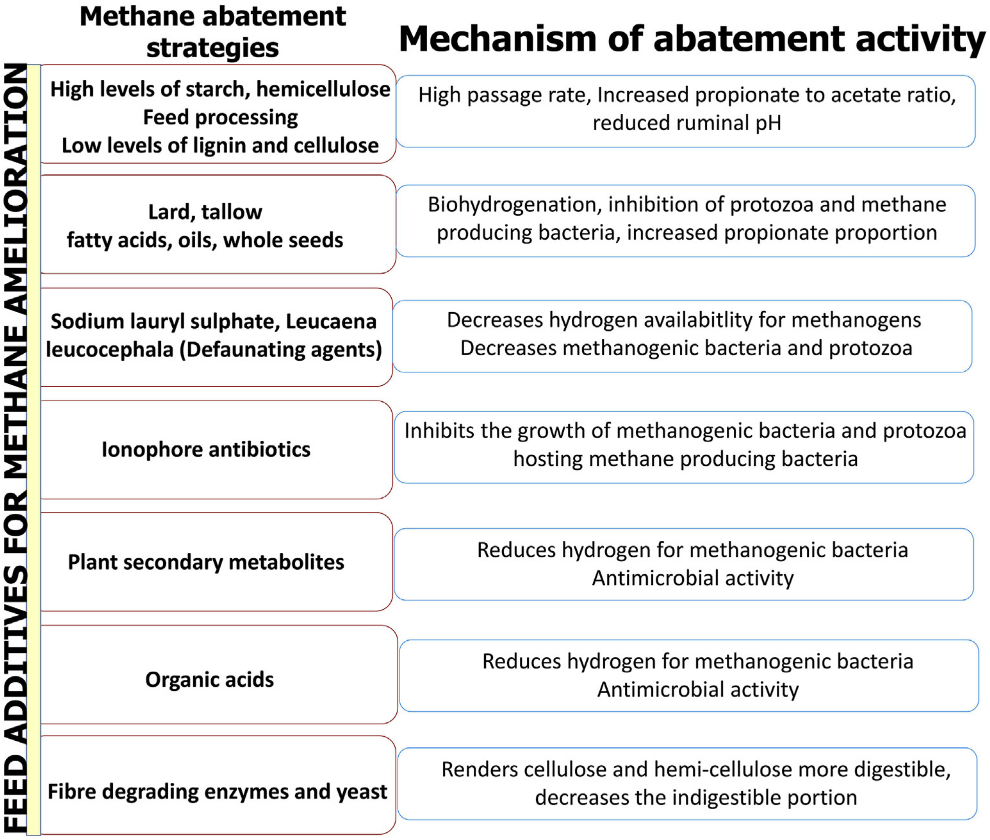


Fig. 6. Dietary strategies and mechanism of CH_4 mitigation activities.

from animal wastes can reduce GHG emission during manure management by over 50% (Amon et al., 2006). The manure from small ruminant, cattle, pig, poultry, horse; and rabbit could be used for biogas generation (Caruso et al., 2019). Cow, buffalo, pig, and small ruminant, produce dung in a range of 15–20 Kg, 18–25 Kg, 1.2–4.0, and 0.9–3.0 kg per day, respectively (Vietnam Biogas Association, 2011). Ngumah et al. (2013) estimated the enormous biogas potential of cattle, small ruminant, pig, poultry manure, abattoir waste, and crop residue as 6.52, 2.3, 0.92, 2.5, 4.42, and 4.98 billion m^3/year respectively. These sources are part of the causes of air and water pollution in some Nigerian cities and towns. On-farm agri-food value chain needs to reduce their dependence on fossil fuels and start utilizing alternative cleaner energy forms such as biogas for cooking and generating electricity. There is a huge potential in biogas production, which can provide fuel for cooking, lighting, and transport. A small-scale biodigester sizes with 20–100 kg dairy cattle dung as feedstock can generate up to 3.5–10 h power for biogas stove and 8–25 h for biogas lamp (National Biogas Program, 2008). This fuel could be a source of renewable energy for nations with limited energy supply. Besides, biogas as cooking fuel would reduce deforestation, thus protecting the ecosystem and more importantly, the climate. In the tropics, livestock manure has a dry matter, nitrogen, and phosphoric acid in a range of 46%–90%, 5–25%, 4–39%, respectively (Ruganzu et al., 2015). Therefore, after the biogas, the remaining effluent can allow the potential for recovery of N and P as biofertilizer. The biofertilizer is made up of undegraded organic matter such as lignin and cellulolytic fiber (Elum et al., 2017). Biofertilizer is often regarded as a better replacement to chemical fertilizer because of its ecofriendly nature unlike the latter (Umeghalu et al., 2012; Elum et al., 2017). Therefore, application of biogas digester residue as fertilizer could help improve crop production and close the yield gap of crop in sub-Saharan Africa, South Asia, and other low-income countries.

4.2.2. *Livestock wastewater treatment or management*

Plants, often associated with microorganisms, are used to mitigate environment pollution through phytoremediation (Coelho et al., 2015). Microalgae is a renewable resource that has a short life and could be grown in wastewater (Acién et al., 2017). The decomposition of livestock faeces and urinary nitrogen produces pollutants such as ammonia and N_2O, which are essential for the growth of microalgae (Mobin and Alam, 2014). Microalgae is capable of assimilating inorganic N and P and transforming them into valuable organic compounds (Dang and Lee, 2018), which could be further used to generate biogas (Barreiro-Vescovo et al., 2018). Treatment of wastewater with *Chlorella* sp. was known to successfully reduce 28–94% nitrogen and Phosphorus (Aslan and Kapdan, 2006; Li et al., 2011). Further, Marinho-Soriano et al. (2009) showed that red seaweed (*Gracilaria birdiae*) reduced PO_4^{3-} by 93.5% and NO_3 by 100%. Similarly, co-cultivation of salmon and *Gracilaria* removed dissolved ammonia by 50% and 90–95% in winter and spring, respectively (Troell et al., 1999). He et al. (2008) attributed the benefit of seaweed in reducing the N_2O pollution to its capability in storing the nitrogen at high concentration. The seaweed acts as an adsorbent by binding pollutants in the presence of sulfated polysaccharides (Arumugam et al., 2018). In addition, cultivating microalgae in wastewater could lead to decrease in N_2O saturation and production because of limiting/decrease in nitrogen oxides (NOx) (Webb et al., 2019).

Meanwhile, water hyacinth is seen as a weed because it invades water bodies - usually polluted water- and can be found in many

African rivers and waterways. The invasion affects the livelihood of farmers, fishermen, and boat operators, whose lives depend on water (Honlah et al., 2019). Water hyacinth invades waterbodies because of in-flow of nutrients (nitrate and phosphate) from wastewater, fertilized farms, and sewage brought by erosion run-off, which supplies nutrients for its growth (Hauser et al., 2014). Interestingly, water hyacinth can even grow on water polluted by oil spillage as seen in waterbodies in Niger Delta region, Nigeria. Because of these advantages, water hyacinth and *Gracilaria* can be used to reduce nutrient in wastewater and even as co-substrate in biogas plant. Apart from biogas generation, water hyacinth could be used as organic fertilizer because it fixes large amount of N and P in its tissue (Degraft-Johnson, 2005), thsu can be used for soil amendment. It is also reported to possess properties that prevent common root-knot disease (nematodes) in tomato and pepper plant (Adomako, 2007). Water hyacinth could also be used as alternative source of biofuel as opposed to wood fuel. Although, water hyacinth contains about 50% of caloric value of dry wood, its abundance makes it a good source of fuel (Ighodalo et al., 2011). Therefore, the growth of water hyacinth on wastewater could be a source of fuel, fertilizer, and energy for farmers and rural households.

In technologically advanced countries, wastewater generated from livestock rearing is recycled and treated to improve water quality, during which N_2O production occurs. Application of carbon fiber (ca. 1 m^3 bioreactor) as a carrier for 45 days in swine wastewater treatment resulted in a reduction in N_2O emission by 85% (Yamashita et al., 2019). The N_2O oxide generated from the control (activated sludge) was 1824 vs. 270 mg/day (Carbon fiber reactor) a much lower emission. The carbon fiber acted as a carrier where microbes can adhere thickly and remain active for longer durations. The microbes belonging to phylum Chloroflexi, which are able to reduce N_2O, are more abundant in the biofilms of the CF reactor (23–27%) than in activated sludge (15%). The continuous supply of nutrients supports the growth of thick niche (thickness >1 mm) and allows the co-existence of both nitrifying and denitrifying bacteria within the aerobic and anaerobic regions of carbon fiber. The lower nitrate and nitrite contents remaining in the wastewater are also responsible for low N_2O. Therefore, inserting CF during wastewater treatment has the potential to reduce N_2O generation and improve water quality. The water could be used for drinking water, aquaculture, or irrigation purpose, thereby increasing the water-use efficiency. Converting waste into resources through waste valorization may contribute to environmental stewardship programmes. For instance, the water hyacinth and microalgae, which could be grown on fecal residue and wastewater, are used for biofuel production. Highly productive microalgae is an attractive technology for bioenergy production (Barreiro-Vescovo et al., 2018). Fuel generated under controlled condition from the use of algae is classified as a third-generation biofuel (Fekete, 2013). Barreiro-Vescovo et al. (2018) have demonstrated the potential of biogas CH_4 from microalgae. Therefore, the potential of using microalgae for phytoremediation and then using it for biogas production should be studied for the feasibility.

4.2.3. Biochar of agricultural waste

The conversion of animal waste and crop residue to biochar through pyrolysis rather than disposing or using them directly for manure purpose could result in improved nutrient recovery, nutrient recycling, and regional food production. Production of biochar from agricultural waste is considered as one of the best options for carbon sequestration, thereby contributing to environmental sustainability through distributed energy generation (Saletnik et al., 2019). Carbon sequestration involves the capture and prolonged storage of atmospheres CO_2 to mitigate global warming and its dangerous impacts (Dhanwantri et al., 2014). Carbon dioxide removal or negative emissions technologies are aimed at sequestering carbon. Reforestation, afforestation, wetland restoration, sustainable agricultural practices, and carbon farming are few methods of carbon sequestration. Soil degradation and declining crop yield have negative impacts on food security and socio-economic development in low- and middle-income countries (Pender et al., 2006). Sub-Saharan Africa will be a key in global effort to sequester carbon in agriculture (Tenningkeit et al., 2012). Restoring carbon is an important effort to reverse declining soil fertility and improve agricultural productivity. Sequestering carbon to improve soil fertility would help to mitigate GHG, reduce malnutrition, poverty, and improve food security by increasing the crop yield. Crop wastes that constitute huge nuisance in highly productive regions could be converted to products with environmental, economical, and agricultural value. Biochar have been made from Brazil nut (*Bertholletia excelsa*) (Lefebvre et al., 2019); cotton husks, eucalyptus residue, sugarcane filtercake, swine manure (Speratti et al., 2018); rice straw (Nisa et al., 2019); cassava residues, corncobs, rice husk, sawdust, coffee husk, and Peanut (Billa et al., 2019); and walnut, loblolly pine wood, pine needle, palmwood, and nutshell (UC Davis Biochar Database, 2019). The pictorial representation of biochar preparation and its potential benefits is presented in Fig. 7.

4.2.3.1. Biochar properties. Biochar is a carbon-rich product from biomass produced at relatively low temperatures (<700 °C) under low oxygen supply (Lehmann, 2009). They contain mineral elements and the structure is influenced by the material and the temperature of production. A typical biochar from poultry litter contains 44.00–46.10% carbon and 2.80–4.90% nitrogen; however, the total proportion of carbon and nitrogen depends upon the temperature used during biochar preparation. The highest proportions of carbon and nitrogen from poultry litter were obtained at lower temperature of 350 °C, while the lowest were obtained at 700 °C with a surface area of 1.10 and 9.00 m^2/g, respectively (UC Davis Biochar Database, 2019). From the same database, it was observed that total surface area varied when the same material was biochar at different temperature. Thus, the pyrolyzing temperature influences the total surface area of a particular biochar biomass. Biochar has alkaline properties because of the negatively charged functional groups (hydroxyl, carboxyl and phenolic group) on its surface, and influences the hydrophobic, hydrophilic, buffering, and ion exchange capacity (Brewer and Brown, 2012; Chintala et al., 2014; Anton-Herrero et al., 2018). The properties and various factors involved in preparation of biochar and their effects on the environment is well documented by three recent reviews (Yuan et al., 2018; Panwar et al., 2019, and Saletnik et al., 2019).

4.2.3.2. Biochar potential or benefits. Biochar has been observed to improve protein levels in livestock (Boonanuntanasarn et al., 2014), reduce ammonia nitrogen emissions in aquaculture (Quaiyum et al., 2014), and improve growth performance in goat, turkey, and broilers (Villalba et al., 2002; Majewska et al., 2009; Fu et al., 2015). At higher temperature (>300 °C) the alkalinity of biochar increases (Chen et al., 2019) and as such, this property of biochar could help in maintaining gut pH of both hindgut and foregut fermenters. The cation exchange capacity of biochar can be influenced by biochar age, temperature of production, rate of decomposition of cellulose, and carbonization processes (Lee et al., 2010; Kalinke et al., 2017), which could further affect the ability to absorb various toxins.

Applying biochar in soil could help control the rate or pathway by which CO_2 fixed by plants returns to atmosphere (Cross and Sohi, 2011; Meier et al., 2017). Biochar usage helps in increasing

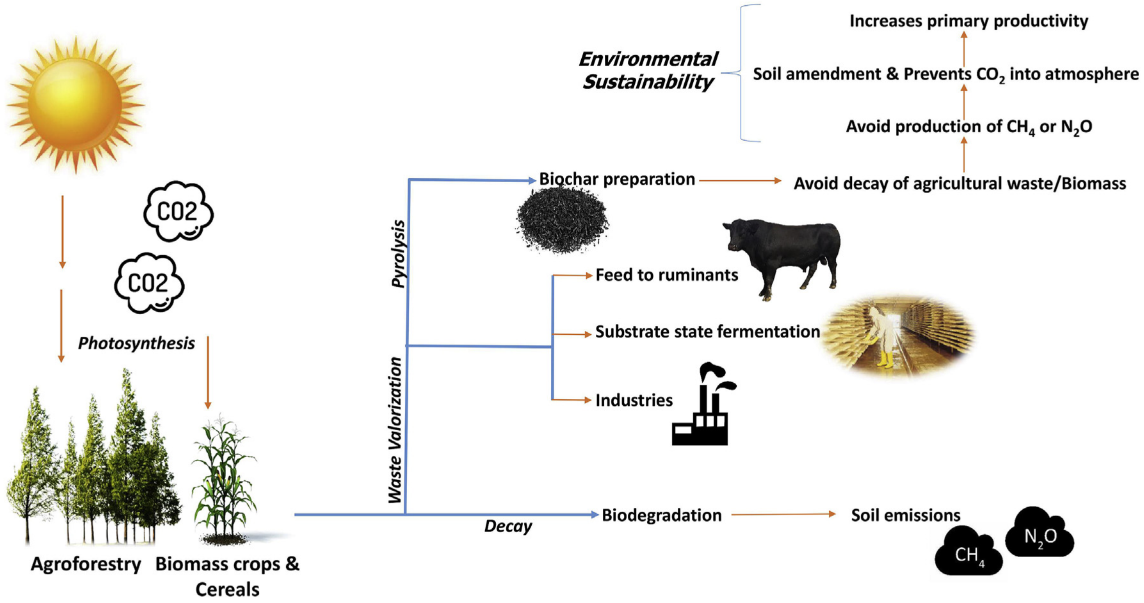


Fig. 7. Preparation and potential benefits of Biochar.

soil organic carbon compared to those from plant residues, compost, and animal manure (Kimetu and Lehmann, 2010). The amount of total soil carbon deposition is primarily influenced by the pyrolysis state of biochar. Complete pyrolysis of biomass will increase carbon input into the soil because the carbon is recalcitrant and the incomplete pyrolised biochar has labile carbon, which has propensity for losses (Bruun et al., 2011). This suggests that the ability of biochar biomass to hold on to carbon (strongly) may be an indicator of its ability to sequester carbon or carbon sequestering potential. High porosity of biochar consequently improves the water holding capacity of the soil and reduces leaching of macro minerals (Fischer et al., 2019). Similarly, biochar improve soil aeration and water infiltration, soil water retention in sandy soil (Speratti et al., 2017). Biochar production could be sustainable as it can be produced from waste and applied as biochar-based organic fertilizer. The highest efficiency of biochar on crop yield may be obtained by applying it to degraded or low to medium fertile soil rather than healthy soil (El-Naggara et al., 2019). Majority of the agricultural lands in sub-Saharan Africa are infertile and are being depleted due to continuous farming, thus draining the nutrients completely. African soils are inherently poorly fertile because they are old and lack volcanic rejuvenation (Bationo, 2009). Furthermore, the effect of biochar on crop yield is influenced by soil conditions (structure, microorganism, deficiency, and water holding capacity) and ways of application to crops (Chen et al., 2019). Therefore, application of biochar must be adapted to local conditions to improve its effectiveness.

4.2.3.3. Biochar application.

Application of biochar (made from bull manure, dairy manure, swine manure, *Pinus* spp, and willow wood) have resulted in increased microbial activity, microbial biomass carbon, and dehydrogenase activity (Kolb et al., 2009; Ameloot et al., 2013). Land spreading of manure from animal production units increases CH_4 (Chadwick and Pain, 1997), N_2O (Meade et al., 2010) and CO_2 (Bourdin et al., 2014) emissions. Amendment of livestock slurry before application could help reduce pollution. Application of cattle slurry on land after amendment by alum, lime, and biochar reduced emission from such land (Brennan et al., 2015). Lime and biochar significantly reduced NH_3 emissions, cumulative N_2O loss, CH_4 emissions, CO_2 emissions in a range of 44–134% compared to the treatments with unamended slurry. Ammonia is known as an indirect source of N_2O emission. Most ammonia that is volatilized from field application is generally redeposited within 2–5 km, among which, 1% proportion will be re-emitted as N_2O (IPCC, 2006). Therefore, after the estimated indirect N_2O emission due to redepostion of ammonia, total N_2O emission was reduced by 69% by biochar. The decrease in N_2O emission from application of biochar-amended slurry could be attributed to increased aeration caused by biochar porosity. This is because N_2O increases as soil oxygen decreases, from 21% to 0% (Zhu et al. (2013). Therefore, biochar of manure and agro-industry waste could help to trap carbon in tropical soil, increase soil carbon, soil aeration, soil fertility, nutrient recycling and reduce GHG emission.

Agroforestry plays an important role in the lives of every individual globally. Apart from the social and economic benefits, the agroforestry systems also helps in sustainable environment (Leakey, 2012). It is important in carbon and oxygen recycling, fuel, construction material, and agro-industrial material. Further, it could play an important role in overcoming poverty, hunger, malnutrition (through fruits and nuts), medicines (herbs, roots, leaves etc), land reclamation, and even climate adaptation strategy. Due to high level of deforestation for industry, housing, fuel and recurring natural fire outbreaks such as in the amazon tropical forest, there has been raised interest in the reforestation. This has caused pledges to support reforestation to sustain the livelihoods and sequester CO_2 (Smith et al., 2016). A study found that low application of biochar (1 t/ha biochar) or biochar plus fertilzer to tropical trees enhanced the seedling survival and growth performance of tropical trees (Lefebvre et al., 2019). This indicate that biochar could be applied for afforestation, reforestation, and forestry plantation even at lower rate. Even, this could be important in reforestation project in desert areas. Thus, biochar application in agroforestry could be a potential tool to achieve sustainable development goal by increasing conservation and reforestation. Care must be taken while applying biochar in crop production. Over application of alkaline biochar is often related to increased soil pH consequently affecting the nutrient uptake by plant. For instance, application of biochar with higher alkalinity increased the soil pH and decreased the maize biomass (Speratti et al., 2018). Similarly, another study found that application of biochar at 1 ton/ha resulted in better performance compared to 5 ton/ha (Lefebvre et al., 2019).

4.3. Shift in management systems of crop and livestock production

Collective organization of the production systems while modifying them as mixed crop-livestock system to derive high-value products will increase extraction of value from their production resources without expansion. Thus, shifting the commonly practiced management systems of crop and livestock production into effective resource utilization systems reduces the potential emissions.

4.3.1. Feeding system or management or production pattern

Mixed farming is common worldwide and could be employed in reutilizing resources, thereby improving nutrient capture. Two-third of total livestock are under the mixed crop-livestock system (56% ruminant), which contribute 64% of global enteric fermentation-based CH_4 emissions while the proportion is 35% for grazing systems and 1% for industrial systems (Steinfeld et al., 2006; Herrero et al., 2013). Since the inception of the millennium, mixed crop-livestock system has played a significant role in global nutrition and regional nutritional security. In the year 2000, mixed crop-livestock system accounted for 69% of the 586 million tons of milk, 61% of 70 million tons of meat, and 61% GHG emission from ruminant units worldwide (Herrero et al., 2013). Furthermore, data obtained from 2001 to 2003 showed that 46%, 88%, and 50% of meat, milk, and cereals, respectively, are produced from the mixed crop-livestock systems (Smith et al., 2013), whereas, the intensive system supplied 45% meat and 21% milk (Steinfeld et al., 2006, Thornton and Herrero, 2010). The mixed crop-livestock system could arguably be regarded as the most important cereal and ruminant production system, because of the volume of its contribution to global nutritional supply, the use of global bioresources, the ability to supply nutrition to all financial classes (rich and poor), and the potential to ensure nutritional security. It could serve as a linkage or bridge the gap between the industrial and subsistence production system, the nutrient secure and nutrient insecure, cushion for crop or livestock losses, and ensure growth of agrarian nations gross domestic product. These reports reveal the importance of mixed crop-livestock system and the need to improve the practices in this system and reduce GHG emission from it to make it sustainable.

Crossbred cattle are known to perform better than local breeds because of their superior genetic potential for growth or milk production. Importation of animals with higher genetic potential is a great idea; however, few unavoidable challenges such as climate change adaptation, technical expertise among farmers, financial capital, and availability of feed resources makes the practice unsustainable. Extensive system is currently practiced in many West African states, which have caused increasing violent controversies between farmers and herdsmen, especially in Nigeria. Extensive production systems and management accounts for the high emission from small ruminants compared to those meant for intensive meat production (Patra, 2014). Introducing a household feedlot production system based on feed from Leucaena grown on-farm is an option of reducing emission intensity from the local breeds of cattle. Feedlot system is considered as a way of increasing the productivity of our animals in West Africa. Switching from native grass to Leucaena feeding in beef system reduced GHG emission intensity from 16 to 57% in northern Australian (Taylor et al., 2016) and Indonesia (Dahlanuddin et al., 2017). In this system, cattle may be fed 100% Leucaena at an average of 5 kg of dry matter (DM) per day. This study shows that it is possible to improve the nutritional value of low-quality crop residues such as maize stover and rice straw with Leucaena. Bharanidharan et al. (2018) showed that feeding ruminant roughages and concentrate separately has the potential to reduce GHG compared to total mixed ration practice. Split feeding of concentrate reduced CH_4 by 13.43%–14.66% while increasing total VFA by 21% than cattle fed total mixed ration.

4.3.2. Intensively recycling or recovery of nutrients

Practices of increasing crop- or animal-based products without following the sustainable techniques would exacerbate environmental pollution and degradation. As a general practice, farmers continue to apply inorganic fertilizer and manure indiscriminately while those that cannot afford such continue to open more virgin lands to increase the yield. Nutrient in specialised farms of either crop- or animal-dominated system are poorly recycled for beneficial purposes and are rather used by nature to constitute environmental nuisance. Nutrient not taken up by crops will be either leached or washed down into water system or may volatilise into the air. Annually, a substantial amount of nutrients are lost through crops at different stages of food chain such as harvesting, processing, packaging, marketing, and consumption. About one-third of edible food is wasted or otherwise lost from food supply every year (Gustavsson et al., 2011). The losses include cereals, root crops, fruit and vegetables, oil seeds, meat and fishes, which accounts for 30%, 40–50%, 20% and 30%, respectively (Sutton et al., 2013). Failing to pass the standardisation test such as expected shape, weight, or color is one of the pivot reasons for food wastage. These wastes (fruit, vegetable and others) contain mineral, vitamin, nutrient and some phytochemicals and could be used as feed for ruminants in emerging and transitional nations, in regions like sub-Saharan Africa, Asia, and South-East Asia. In this way, livestock could also help to retrieve lost nutrients and recouple them into the food chain, thus mitigating environmental pollution. The N and P efficiency, showed that amount of nutrient retained in livestock is influenced by the production intensity of the system, which varies from 5 to 30% of total nutrient intake while others end up excreted (Teenstra et al., 2015). Therefore, integration of different nutrient flows by linking livestock waste with crop system or vice versa could become an avenue to achieve higher nutrient usage efficiency.

4.3.2.1. Plant waste and manure. The global warming potential of plant-based food sources is far lower than ruminant-based meat or milk. In India, livestock and rice production are the primary sources of GHG emissions in agriculture. The potential global warming of rice, mutton, and milk are 5.65, 45.54, and 2.4 kg CO_2 equivalents, respectively, whereas in the case of cereals (other than rice), fruits and vegetables is less than 1 kg CO_2eq kg/product (Vetter et al., 2017). These facts reveal the undeniable significance of herbivores in global warming (Ripple et al., 2014), which further strengthens the encouragement of plant-based products consumption compared to meat. Nevertheless, animal-based diets are important sources for converting human-inedible resources to protein of higher biological value. For instance, kitchen and party wastes are considered as economical food for pig fattening in many third world countries. Livestock products are valuable agricultural commodities for nutritional security, as they provide about 17% and 33% of global kilocalorie and protein (Rosegrant et al., 2009). Therefore, recycling or retrieving nutrient could help reduce pollution. Even nature itself is more of a mixed flora-fauna system of existence, which causes nutrient recycling in our ecosystem. Poultry manure, agro-industrial byproduct, fruit- and vegetable-processing wastes, baby cornhusk, and sugar beet wastes have been reported to be useful in feeding livestock (Wadhwa, and Bakshi, 2016). Ibáñez et al. (2016) fed Murciano-Granadina goats with orange pulp and soybean hull as a substitute for barley. The authors found a similar amount of urinary nitrogen losses in the goats fed with orange pulp and barley, while the soybean fed goats excreted 20% more nitrogen than barley. In an Indian study, Wadhwa et al. (2006) fed cauliflower leaves, cabbage leaves, pea pods, pea vines, and green oats to goats. The N-excretion as a percent of intake was 69.9, 84.8, 65.1, 83.2, and 83.8 for cauliflower leaves, cabbage leaves, pea pods, pea vines, and green oats respectively. The urinary nitrogen compared to intake was 44.98%, 74%, 45.45%, 50.4%, and 48.18% for cauliflower leaves, cabbage leaves, pea pods, pea vines, and green oats, respectively. The study discloses the fact that vegetable wastes may be used as animal feed for nitrogen recovery. Further, a recent study showed that the replacing conventional feed ingredients with unconventional resources might reduce the carbon footprint of the diet and total global warming potential contributed by the ruminant species (Reddy et al., 2019).

The livestock sector can transform from being a contributor of pollution to a possible solution by providing food security, nutrient cycling, and enhancing resource-use efficiency while reducing malnutrition and poverty. Conversion of agricultural wastes rich in cellulose, hemicellulose, and phytochemical compounds to animal feed, biofertilizers, and biogas could go a long way in reducing pollution. Application of farmyard manure can improve grassland carbon stock and reduce CH_4 and N_2O emission than slurry when mixed with low-quality dry grass (Maeda et al., 2013; Mori, 2018). Mori (2018) assessment showed that application of farmyard manure reduced overall net GHG emissions and intensity by 36% (6.9 Mg CO_2-eq/ha/year) and 41% (0.89 Mg CO_2-eq/Mg), respectively. Similarly, agricultural waste releases mineral nutrients, CH_4, N_2O, non-GHGs - ammonia and dinitrogen, into the environment during composting (Andersen et al., 2010; Nigussie et al., 2017). However, managing the timing of manure addition could influence the total quantity of GHG emissions during composting. For instance, adding manure after the thermophilic phase at a temperature below 30 °C reduced CH_4, but increased N_2O emission (Nigussie et al., 2016). The thermophilic temperature favours N_2O production (Hao et al., 2004). In view of this, we suggest that role of biochared manure in reducing the excretion of volatile nitrogen and N_2O emission need to be further investigated.

4.3.2.2. Fungi (mushroom). The fungi are able to breakdown cellulose and lignin to enable easy access to the nutrients bound to those structural carbohydrates. The degradation ability of fungi contributes well to the human food and animal nutriton especially ruminants. The ability of fungi to degrade fibrous or lignified substances is evident in the growth of edible and inedible mushrooms from dead tree trunks and branches. Fungi may also be grown on straw, cottonseed hulls, corncobs, peanut shells, coffee pulp, and cotton from the textile industry (Sanchez, 2010). Inoculating agri-industrial wastes with Pleurotus (oyster mushrooms) could help to harness nutrients in waste to produce high-quality products like mushroom. The residues of these products after human consumption could be fed to ruminants to obtain a product of higher biological value. The waste from such mushroom is known as spent mushroom substrate and when used for compost making, the substrate increases the mineral status of the soil apart from promoting the yield of cereals (Courtney and Mullen, 2008). Nontoxic fungi such as *Pleurotus ostreatu*, *Trametes versicolor*, *Aspergillus awomori*, *Aspergillus terreus*, *Pleurotus eryngii*, *Pleurotus sajor-caju*, *Pleurotus eous*, *Phanerochaete chrysosporium*, and *Lentinula edodes* could also be used to enrich the nutritional value to crop wastes. These fungi could improve nutrient recycling and animal nutrition by increasing crude protein concentration in straws and cellulose digestibility (Shrivastava et al., 2011; Zhao et al., 2015; Thi Huyen et al., 2019).

4.3.3. Food processing and preservation

Although several methods exist in improving the food security, improving soil fertility and irrigation of farmland are best known to decrease the yield gap, especially in Africa and South Asia regions. To reduce poverty, farmers must make enough income from their products or off-farm means. However, farmers find it difficult to make a decent income from their products due to the poor processing, storage, and transportation facilities, which leaves them vulnerable to the marketers. The vulnerability of farmers in developing countries could be reduced by paying more attention to harvesting, transportation, and processing phases of production. A lot of food produced never makes it from farm to mouth, and are lost in between production, post-harvest, processing, and distribution. FAO (2011) reported that the wastes from sub-Saharan Africa, South Asia and Southeast Asia accounted for a proportion of about 120–170 kg out of the 460 kg per capita production of edible parts of food. This accounts for about 32% waste along the food chain with more than 80% of the waste occurring at the post-harvest and processing phase. Overall, more than 40% of food losses in developing nations occur at the post-harvest and processing levels, whereas, the same proportion is lost in developed countries at the retail and consumer level (FAO, 2011). Certainly, reducing food losses at harvest and processing level is necessary for food security in developing nations. Farmers can also make more income if they have technical knowledge of preserving their products such as fruits in season of abundance and sell them - mostly during off-season, after their conversion to high-value packaged products while preserving the nutritional and organoleptic properties. An example of processing is the garri and fùfú products derived from cassava in Nigeria or concentrated orange and mango jam at Songhai farms in Benin republic, West Africa. Increased crop processing and preservation could lead to the development of new food variety and product development. Therefore, increased food processing and reducing post-harvest loss is another form of securing food availability. Developing countries, especially those in sub-Saharan Africa and South Asia, must strive to establish the Agri-livestock food value chain to promote food security by reducing food waste.

4.3.4. Integrated farming system

Nature itself has created a prototype for which humanity can model its food production systems and recycling of its nutrient without any wastage causing pollution. Integrated system of production is important from the resource-base management, environmental, productivity per unit of input, and perhaps, economic point of view. Changing circumstances necessitate the need to take a different approach to management practices. The integrated farming system does not necessarily mean integration by location; it essentially implies integration of resources such as manure, wastewater, crop residue, and animal waste with livestock feed (Fig. 8). Benefits of integration of agricultural resources are synergistic (Little and Edwards, 2003) and involve lesser external input with less negative environmental impact compared to the intensive system (Kautsky et al., 1997). Integrated system permits value to be placed on waste and eliminate specialization and separation of agrosilvo and aqua-livestock production system. For instance, resource-exchange could be a means of integrating spatially separated but resources-use integrated agricultural system. The constant clashes between herdsmen and farmers in North Central Nigeria could be resolved if there is a memorandum of understanding between both parties to share resources. In this regard, there could be an exchange of faeces, crop wastes, grains, and animal products between both parties where they highlight resources that they have independently, but could be shared in a symbiotic manner. Farmers may collect some tonnage of manure while

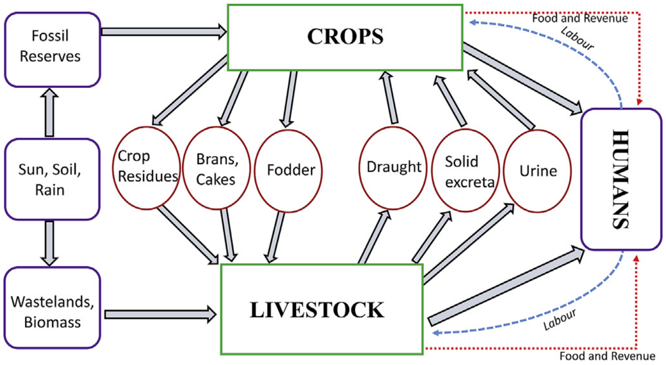


Fig. 8. Integrated resource use for crop and livestock.

herdsmen would use their crop left over, such as stalk, hull, and fodder to feed their animals. This could work if they are not presented with any political and religious undertone. Promoting the sustainable livestock system requires an integrated approach that combines multiple expertise such as agricultural production systems, ecology, biology, water systems, conservation, and economics (FAO, 2016). The integrated farming system is one of the essential solutions for sustainable livestock system in regions, such as Africa where nutrient input and usage efficiency is low (Sutton et al., 2013; FAO, 2017).

4.3.4.1. Model integrated farm. Integrated farming system of agriculture could be a means of recycling nutrients to improve the manure usage and reduce carbon footprint of feed production. Following zero wastage system, nutrient recycling could contribute to sustainable production systems, especially in regions with too little access to nutrient. An ideal functional model for this method is Songhai farms of Benin republic, West Africa. The centre has been successfully following the integrated farming system by coordinating all stages of agriculture from production, breeding, harvesting, processing, marketing, and nutrient recycling. In zero-waste system, crop and livestock wastes are composted and applied to the soil for fertilization without using the inorganic fertilizer. Further, the inedible animal parts such as intestines, fish gills can be allowed to decay for the growth of maggots, which are considered as protein-rich feed supplements in aquaculture systems. In addition, the fecal waste from humans is biodegraded into useful organic form with water hyacinth. Water hyacinth is further harvested and used as material for biogas, which is directly used for cooking or electricity purpose. Other wastes from the system such as palm fruit bunch can be inoculated with edible mushroom, which helps to harness nutrient to grow products of higher market value. These spent palm fruit bunch are used as fuel during rice or oil palm processing, and is eventually converted to potash or ash and used to fertilize the soil.

4.3.4.2. Water recycling or integration. According to CAWMA (2007) the improvement in water productivity is also part of sustainable agriculture. This implies that more valuable food products are derived per unit of water input in agriculture. An integrated system of fish farm and pig, duck, chicken, sheep or fish-cum-duck-alfalfa-rice was recommended by (FAO/IPT (1992) to improve water productivity, nitrogen metabolism, nutrient recycling, and efficient resource utilization for production among rich and poor farmers in urban and rural areas. Wastewater from livestock and cultivated aquaculture pollute the environment and waterbodies because of the nutrients embedded in them. Wastewater used for cleaning livestock could be used for fisheries and those from fishponds can be used for crop irrigation to redistribute nutrient and reduce nutrient losses. Therefore, proper distribution of this wastewater among these systems rather than drain them into natural water bodies would be significant. Wastewater could be used to grow high-value plants like vegetables or as irrigation material, especially in dry season. However, CAWMA (2007) recommended that risk of contamination should be kept at the minimum level while using them for growing edible foods because of the risk of food-borne pathogens. Although the use of wastewater for irrigation purposes was traditionally considered as an efficient management strategy for environmental sustainability, few studies revealed negative aspects of water reuse in agriculture. The research works claim that water reuse may alter the microbiota and biomass apart from affecting the soil texture properties. In this regard, the FAO has published specific guidelines and requirements to be followed while reusing the treated waters, which were classified by the crop variety. The potential benefits, limitations, health risks, and viable approaches to wastewater reuse was well discussed in an extensive review by Jaramillo and Restrepo (2017). Furthermore, the replacement of conventional feed ingredients with agro-industrial byproducts and unconventional resources such as urea is suggested as one of the best methods for reducing virtual water trade (Reddy et al., 2019). The authors also stressed the importance of estimating ingested-, preformed-, metabolic-, or faecal-water concentrations while conducting any *in vivo* trials to know the water footprint of the feed.

4.4. Shifting to animals and crops with less environmental impact and high adaptation

4.4.1. Animals with high adaptations

Small ruminants are of economic importance among livestock farmers in Oceania, Asia and Africa. Sheep and goat represent more than half of global ruminant population (FAO, 2016) and over 50% of the world's small ruminant reside in arid region (Monteiro et al., 2018). Their production system emits 6.5% of total GHG produced by livestock (Marino et al., 2016). World CH_4 emission of sheep and goat is 90.87% and 93.02% lower than in cattle (71,910 Gg) (FAO, 2016). Further, the CO_2-eq of sheep and goat production is 72.98% and 79.36% lower than that of cattle (510,106 Gg CO_2-eq) (FAO, 2016). In the livestock sector, it is estimated that, beef cattle have a major share of 41% of GHG emissions, while dairy cattle, swine, buffalo, poultry, and small ruminants produce 20%, 9%, 8%, 8% and 6%, respectively (Gerber et al., 2013). In comparison, the emission intensity of beef cattle vs. sheep and goats is 71 kg CO_2-eq/kg of carcass weight vs. 6.9 kg CO_2-eq/kg fat and protein corrected milk (Forabosco et al., 2017). This indicates that CH_4 emission intensity per kg of final product of small ruminant is lower than cattle. In addition, their abundance in arid region shows their ability to adapt to high temperature (Hyder et al., 2017a). Adaptation of livestock to heat stress is an essential practice in sustainable livestock farming because of the higher CH_4 produced from heat stress susceptible animals (Hyder et al., 2017b). The adaptable characteristics alongside, the potential for lower emission intensity could make the small ruminant rearing an alternative to large ruminant farming where red meat is still in demand. Among the small ruminants, goats are tolerable to heat stress, and hence desirable species to rear at high temperature zones (Reddy et al., 2019). Exploiting the genetic potentiality by upgrading the local sheep or goat with genetically superior breeds may still lessen the global warming potential per unit meat produced. In sub-Saharan Africa and other global regions with extreme environmental conditions (*i.e.,* hot or harsh environments), the use of local genetic resources in developing countries, represent a better, self-sustaining solution, than the import of highly improved animal with low adaptability

(Boettcher et al., 2015). Local genetically superior breeds may be a better replacement of exotic breeds because of the high tolerance of the local breeds to regional diseases. For instance, a breeding company in Nigeria produced a dual-purpose multicolored chicken breed, known as Noiler, to address the challenges of food insecurity and financial dependency among the rural populace. They have high heat tolerance, hardiness, resistance to common diseases, rapid fattening capacity (3–4 months) and require low-quality feedstuff to produce meat and egg. Despite the requirement of long period for maturity, the improved birds could be substitute for local chicken (e.g. Fulani and Yoruba ecotype) which are small with low growth rate and carcass yield. The continuous efforts to improve the livestock's yield will be a lasting mitigation tool. A conscious intentional effort to improve the yield from livestock could be achieved by genetic improvement and nutritional manipulation. Asian region and sub-Saharan Africa have huge potential to fill its nutritional gap and its supply volume by increasing the cereals, milk, and meat production and cereals.

4.4.2. *Crop with high adaptation*

Farmers should plant new varieties (mostly abandoned or less cultivated crops) that are adapted to drought, erratic rainfall, and climate change. Millet, sorghum and African rice are available grains adapted to sub-Saharan Africa. Millet, on its own, requires less water than rice and is richer in protein (ICRISAT, 2000). Cereal cultivation needs more intensification because the yield (ton) per area (ha) is low. Between 2000 and 2017, data showed that there had been a general increase in the ratio of yield per area harvested for maize, millet, wheat, sorghum, and paddy rice. Many of these increases have been accompanied by land expansion rather than enhanced yield per unit of area harvested, except for wheat, whose harvested area slightly increased. In 2000, ratio of yield per area harvested was 2.3, 1.8, 1.75, 0.87 and 0.65 tons/ha of paddy rice, maize, wheat, sorghum and millet (pearl and finger), respectively, while in 2017, the ratio increased to 2.44, 2.07, 2.60, 1.00, 0.66 tons/ha for paddy rice, maize, wheat, sorghum and millet (pearl and finger), respectively (FAOSTAT, 2000, 2017). There is need for a germplasm improvement and agronomic practices improvement of sorghum and millet where cultivated. Emphasis must be laid on cultivating sorghum and millet because of the other nutritional benefits derivable from it and its ability to produce under harsh conditions. Another unpopular rice species is *Oryza glaberrima* also known as Africa rice. Although it has not been properly developed as much as Asian rice (*Oryza sativa*), it is highly used in the Southwestern region of Nigeria. Characteristically, the seed of this rice is hard and breaks easily, difficult to mill and has lower yield compared to its Asian counterpart (Linares, 2002). Yet, *O. glaberrima* has higher resistance to diseases and pests, tolerates fluctuations in water depth, iron toxicity, poor soil quality, severe climates, and controls weed (Linares, 2002) and importantly matures faster than Asian type (NRC, 1996). The crossing of *O. glaberrima and O. sativa* at West African Rice Development Association (WARDA) resulted in a rice variety with 30–50 days earlier maturity, increased nutritional quality, retained African rice taste, and increased yield by about 0.5 tons per hectare without major input (Linares, 2002). Therefore, with proper agronomic management and input, this rice yield could be an asset for African agriculture and perhaps in other regions too. These crop breeds should not be allowed to be "lost", and they could be kept at gene banks for future use. Presently, African rice is more expensive than Asian rice in Nigeria; however, improving the rate of cultivation, yield, mechanization, and biotechnological advancements may reverse the present scenario by decreasing the cost of African rice. Cultivation of these crops should be encouraged and developed in arid, semi-arid, water-scarce, and drought-prone area of the tropics in Africa. Farmers, academic, and specialised research institutes must improve their agricultural management practices to derive more yield with low water footprint, especially in case of arable crops, which depends largely on rain-fed agriculture. Except in Southern Africa, the crop yield is low in most of the African nations, and hence, the opportunity for improvement is immense in these regions (Rockstrom et al., 2003). The South African countries, primarily rain-fed, comprise improved crop yield per unit of water input (Mekonnen and Hoekstra, 2011). It is noteworthy that other regions of the world depend largely on rain-fed agriculture with about 81% of the water used in crop production from green (rain), except arid region, which depends on irrigation sources (Mekonnen and Hoekstra, 2011). Therefore, it is necessary to improve crop yield to enhance the efficiency of rainwater or rain-fed agriculture without resorting to blue water system of food production. Shortly, limited rainfall and increased dryland on the globe forces the dependency of arid region farmers on rainfed crops alone. African nations should add African rice, millet, and sorghum as part of the mandate crop in their national agricultural research institute just like Cocoa Research Institute (CRIN) and International Institute of Tropical Agriculture (IITA) both in Nigeria, International Livestock Research Institute (ILRI) in Ethiopia and Kenya. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has a mandate for sorghum, pearl millet, and finger millet, to conserve, analyse, and breed; however, ICRISAT alone is not enough for the enormous task ahead. African nations cannot continue to depend on aids and interventions from foreign nations. It is disheartening that despite Africa's dependence on agriculture, many sub-Saharan nations are at high risk of food insecurity. Further, these nations are far from self-sufficiency in cereals, which is less than 0.8 in many regions, though the countries have the highest projected population increase by 2050 (Van Ittersum et al., 2016). Sub-Saharan African leaders must take hands-on measures against reoccurring incidences affecting food availability and affordability such as international market price fluctuations and food scarcity caused by war etc., be intentional and non-political in curbing the growing menace of hunger and malnutrition. African nations and other emerging regions at higher risk of global warming effect must be proactive and act fast, in both research and development, mitigation strategies, education, policies, adaptable crops and animals to withstand and cope with the unfolding effects of climate change. Emerging nations must conduct need-specific and applied research to address national and regional problems about food insecurity, malnutrition, mitigation strategies, and nutrient scarcity or pollution. Research institutes must develop new cultivar with superior properties such as drought resistance, disease resistance, and shorter maturity to perform on lesser inputs, unlike, traditional varieties. There is urgency in the need to increase research in food crops and to ensure self-sufficiency or to reduce the tonnage of cereal import, which affects nation and continental foreign reserve. Commercial and smallholder farmers should be encouraged to cultivate finger millet, pearl millet, and sorghum for food and feed to reduce the competition. Developing countries must use the bioresources (crop and livestock) that have adapted to their biophysico- and environmental conditions.

4.5. *Insect farming*

The conventional practice of producing feed ingredient, especially protein sources, for livestock and aquaculture is no longer a sustainable system of production because of its environmental cost and competition with food. Due to the less environmental impact compared to other protein sources such as whey, egg protein, fishmeal, insect farming is projected as a sustainable alternative to all conventional methods of feed production (Lock et al., 2018).

Insect farming technology is a potential tool in many populated nations for generating valuable biological products of high-quality protein, which could be used for animal feed (Lalander et al., 2014). In addition, the prospects of producing high-quality protein with low water footprint compared to livestock (Halloran et al., 2018) makes insect farming of interest. Insect farming technology is a potential tool for generating valuable biological products of high-quality protein if fed to livestock. Insects are healthy, environmentally friendly, and require low-tech and low-capital for production (Shockley et al., 2018). Nevertheless, insect consumption is not odd. In African countries like Nigeria, grasshopper, winged termites (*Macrotermes bellicosus*), and African palm weevil larvae (*Rhynchophorus phoenicis*) are readily consumed by humans.

4.5.1. Benefits of insect farming

The insect farming provides access to low-cost and high-quality protein for animal feed. Nutritionally, insect meal contains 40–70% protein and 5–40% fat (Rumpold and Schluter, 2013). Besides the nutritional benefit, insect-derived products such as fat, oil or chitin have shown great potential as immunostimulants and gut modifiers (Gasco et al., 2019). The immune-modulating functions of insect-based products could extend their use in animal health, microbial modulation, and perhaps as feed additives. Presently, Black soldier fly larvae (*Hermetia illucens* L.), *Tenebrio molitor* L. (yellow mealworm) and house fly (*Musca domestica*) are mainly used as animal feed for monogastric (Biasato et al., 2017) and fishes (Smárason et al., 2017). The protein quality of houseflies and black soldier flies is comparable to fish meal and soybean meal (Van-Huis and Oonincx, 2017). In low income countries such as Nigeria, the soybean meal, groundnut cake, and fish meal used in monogastric and aquaculture are imported from Europe, Denmark, United States, and neighboring countries. Therefore, insect meal protein could help the developing countries to reduce dependence on the importation, thus promoting the economic and environmental sustainability. Besides, the resources required to produce these insects have less impact on the environment compared to the resources (inorganic fertilizer, land, water, opening of virgin land) required to produce traditional concentrate ingredients. Therefore, insect farming could be a means of harvesting nutrient from agricultural waste, manure that causes environmental pollution and as an alternative source of high-quality protein. Establishment of insect farming at large scale is an effective way for waste valorization.

4.5.2. Materials for insect farming

One more advantage of insect farming is the sustainable utilization of bio-resources such as waste from agriculture, industries, and households, which is affordable by small- and medium-scale farmers. Insect larvae of housefly grown from manure could serve as live feed for fishes and serve as an alternative, but valuable nutrient feed for resources poor farmers. According to the statistics given by FAO (2013), 27% of the global agricultural products, which account for 1.6 billion tons, are being wasted per annum. As most of the insect species can use nutrients from organic waste, adopting insect farming could be a promising alternative to prevent the loss and conversion of low-quality organic byproducts into high-quality proteins (Van-Huis and Oonincx, 2017). The type of agro-industrial byproduct to be used as substrate depends upon the species of insect. The species of insect and kind of diet required is depicted in Fig. 9. Mealworms can be raised from waste of fruit and vegetable or by-product of brewing industry (Ramos-Elorduy et al., 2002; Oonincx et al., 2015). Black soldier fly can use manure of livestock as a source of nutrient for growth (Newton et al., 2005; Oonincx et al., 2015) and eliminate the presence of *Escherichia coli* and *Salmonella enterica* in manure (Erickson et al., 2004; Liu et al., 2008). Barragán-Fonseca et al. (2018) have demonstrated that Black soldier fly could be grown from organic waste-based diet such as grape pulp, potato peels, bean seeds, cabbage leaves, and old white bread. The house fly larvae can be grown rapidly to produce high-quality protein by

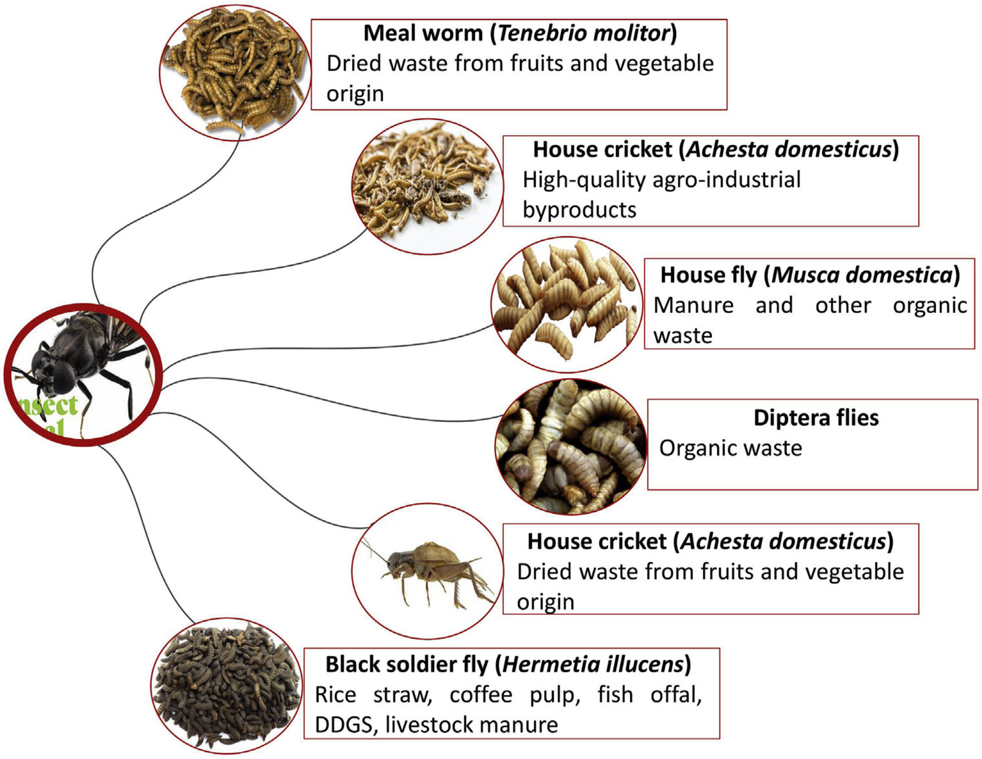


Fig. 9. The species of insect and kind of diet required as substrate.

utilizing low-cost organic waste such as manure (Pastor et al., 2015).

5. Conclusion

To ensure sustainability, food and feed production resources such croplands, forests, waterbodies, and aquatic ecosystems need to be protected from pollution, contamination, and excessive nutrient mining. Integration of agricultural production has a huge potential to enhance nutrient recycling or recovery. Asian region and sub-Saharan Africa have huge potential to fill its nutritional gap, but must accomplish the needs with eco-friendly practices. The practices such as increased use of biochar, anaerobic technology, integrated agricultural systems, waste valorization, and insect technology should adopted as sustainable farming practices in the near future. Further, algae has enormous potential to reduce CH_4 emission form ruminant and recover nutrient from wastewater. The mitigation options mentioned above could help in lowering the GHG and increasing the soil's carbon storage ability, nutrient recycling, and nutrient recovery. Application of biochar on poor soil could help to improve the agronomic value of such land. Researchers in developing nations must strive to improve or modify the existing traditional knowledge of agricultural practices that have been adapted through centuries and perhaps, millennia of practices rather than discarding them for new practices. Despite their potentialities, such efforts only bring short-term solutions and are often neglected in the long-term. Similarly, nations capable of producing “green” food products and feed ingredients would benefit financially in the future. Developing nations must adopt technology of scientifically advanced nations, but adapt it to the local conditions to ensure its acceptability. Regional pollution needs local technology to correct it. Global pollution needs diverse regional solution coming together to culminate in global environmental solution. We suggest that in regions with high pollution due to livestock productivity and/or poor manure management, policies should be put in place to ensure that all farms in that regions have a biogas plant chamber especially on pig and ruminant farms. Furthermore, a national project could be put in place especially in rural communities to have portable biogas digester in each household. In addition, even in urban and peri-urban centers, biogas plants could be used to convert kitchen wastes to methane gas for cooking. Eco-friendly agriculture is possible and would be essential to reduce agricultural environmental risk. Despite the suggestions regarding the recycling of agricultural waste as animal feed or as fertilizer, it will be logical to reduce the volume of waste globally and find economic ways to transport excess food supply to food-insecure regions, which is essential for survival of humanity - and help to reduce undernutrition while addressing food wastage. The conclusion of the topic is that sustainable agricultural production is possible in low- and middle-income counties, only if, the commerical and smallholder farmers are ready to change their current farming practices and adopt new eco-friendly methods.

Conflicts of interest

The authors declare no competing interests.

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