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REVIEW ARTICLE

Challenges and opportunities for agricultural sustainability in changing climate scenarios: a perspective on Indian agriculture

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Abstract

Increasing population and related food demand always remain the most imperative challenges for the developing world. It could only be attained by an increased agricultural production based on external inputs like mineral fertilizers and pesticides during the twentieth century. The green revolution-based modern agricultural practices have resulted in the substantial increase in grain yield at the cost of natural resource degradation. The externalisation of agriculture led to a considerable decline in soil fertility and environmental resilience. It calls for a different approach which should educate the farmers to utilise their traditional knowledge to produce more grains using less external inputs. This approach is known as sustainable agriculture which is the need of the hour, at present. The sustainable agriculture practices are derived from the amalgamation of traditionally adapted healthy practices with a modern development of agricultural systems. Thus, sustainable agricultural practices are supposed to be resource-conservative and resilient to the present climate change scenario. Moreover, a higher proportion of traditional inputs either in the form of resources or the knowledge may encompass the socio-economic balance among different societies. In this review, a brief insight has been given on the concept of sustainable agriculture, its need in the present scenario and a critical assessment in terms of challenges and opportunities for overall sustainability in developing nations by considering India as a model country. How the integration of traditional knowledge and modern agriculture practices will improve the agricultural productivity, soil quality and health as well as socio-economic balance, has also been discussed in terms of research opportunities.

Keywords Biodiversity · Ecological agriculture · Food Security · Green Revolution · Interaction · Organic farming

Introduction

Agriculture, the sole provider of human food, is the world's largest industry and major land-use with a global spread on ~ 40% available land (Ramankutty et al. 2008; Chel and Kaushik 2011; Foley et al. 2011; Sah and Devakumar 2018). Agriculture plays a central role in the economic development of a country (Bose and Mondal 2013). Moreover, the crop-based food products constitute ~ 78% of the average per capita energy needs worldwide, whereas other food sources such as milk, eggs and meat constitute another 20% (Brevik 2013). Thus, the dietary demand of growing population is the basic need and it can only be achieved by increasing agricultural production. As per the Ministry of Statistics and Programme Implementation, Government of India, agriculture and its allied sectors contribute ~ 17% to the gross domestic product (GDP, for the years 2009 and 2017). Moreover, it provides about two-thirds of the employment in India (Directorate of Economics and Statistics 2016). Agriculture is the principal livelihood option for over 58% of rural households in India (Food and Agriculture Organization, FAO 2015). These dimensions of agriculture are depicted in Fig. 1. Thus, growth in the agriculture sector is directly linked with the employment generation and poverty eradication in developing economies (Srivastava et al. 2016). Further, this industry faces a number of challenges and is developing continuously by adapting several measures to cope up with diverse challenges (Fig. 2).

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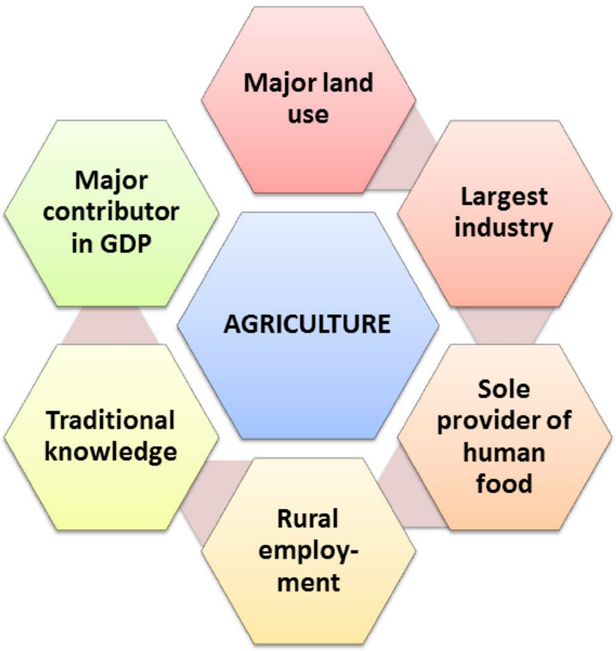

Fig. 1 Importance of agriculture in present scenario

The population of India is expected to reach 1.5 billion by 2050 with a current decadal growth rate of ~ 18% (Ministry of Home Affairs 2011). The increasing population accelerated the pressure on natural resources throughout the world, but more specifically in India which has only 2.2% of world geographical area and supports 15 and 18% of livestock and human population, respectively (Ministry of Agriculture 2015). Of the total land area in India, only 46% is available as cultivable land. Cereal (mostly rice–wheat cropping) cultivation accounts for ~ 75% of the cultivable land (RWC 2005). To increase the agricultural production during the latter half of the twentieth century, green revolution was introduced in India (Borthakur and Singh 2013; Singh et al. 2017). It was originally based on three principles, i.e., people need to eat, land resources are limited, and thereby increasing the yield through external inputs was a necessity (Lobell et al. 2014). Since the introduction of green revolution, the area under cereals has decreased from 38 Mha (million hectares, in 1950–51) to 31 Mha (in 2003–04), while the production increased more than two times [from 15 MT (in 1950–51) to 38 MT (in 2003–04)] during the same time interval due to yield improvement from 408 to 1228 kg ha^{-1} (Ramakrishna and Rao 2008). Therefore, green revolution

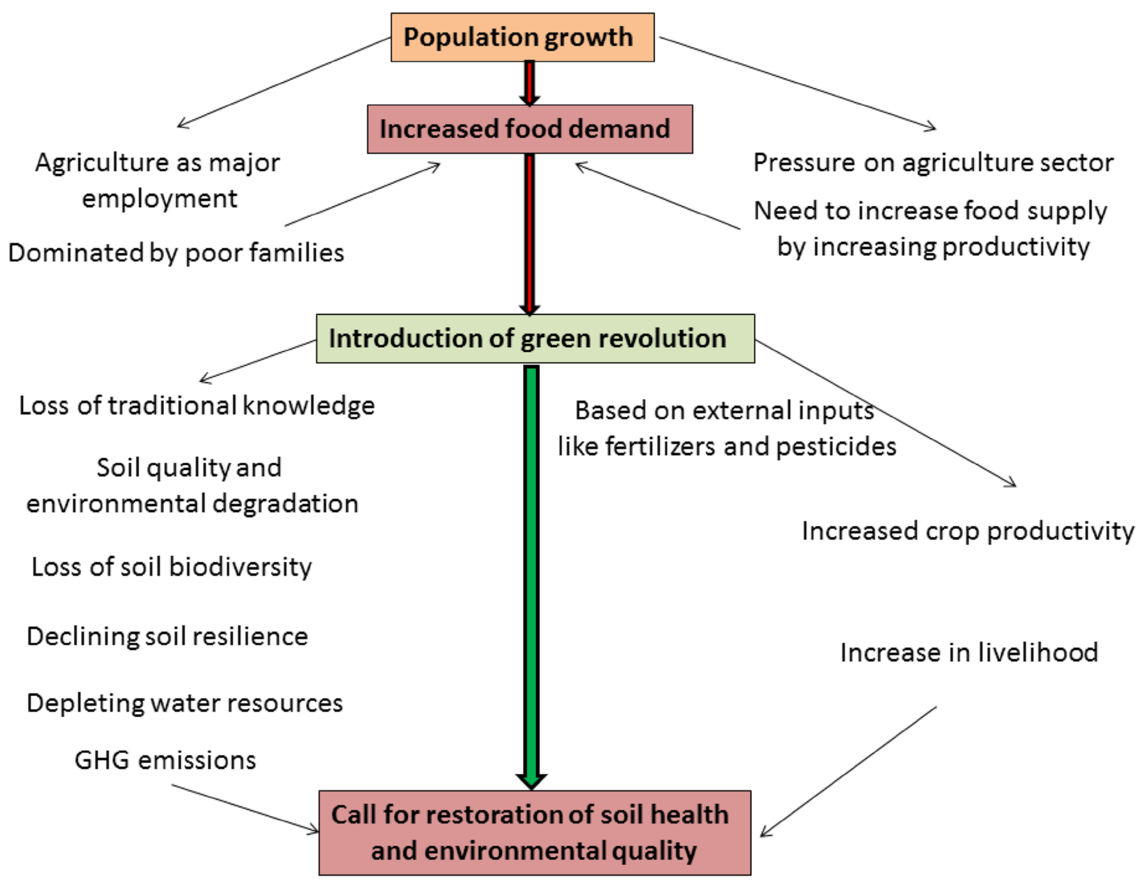

Fig. 2 Challenges to the agricultural sector

led self-sufficiency in food production in India was taken as a role model for several developing countries for reducing hunger and increasing rural prosperity (Bose and Mondal 2013). Though agricultural management based on green revolution practices led to substantial increase in food production, the later consequences in terms of undesirable environmental degradation resulted in the critical scrutiny of these agricultural practices. Thus, an urgent need of ecological agriculture or sustainable agriculture has been suggested by the policy makers (Srivastava et al. 2016). This review has been developed to provide a thorough understanding on the agricultural sustainability by discussing the challenges to the agriculture (after green revolution) sector and the measures to overcome those challenges (opportunities) under climate change scenario with special emphasis on Indian agriculture.

Challenges for Indian agriculture

As stated earlier, the studies reported a twofold increase in the food production during the first 20 years of the launch of green revolution in India. This radical growth was achieved by seven fold and 375 fold increase in the consumption of chemical fertilizers and pesticides, respectively (Singh et al. 2016a). This reckless development had some devastating effects (Bose and Mondal 2013). The external input-driven approach subdued the importance of internal regulation in the agro-ecosystem functioning, biological interactions, soil health and overall environmental sustainability (Srivastava et al. 2016). Thus, it resulted in a significant decline in soil quality and its multi-functionality (Singh 2000). Further, the positive effects of green revolution in the form of instant increase in food production at that time have gained a plateau as the yield is not rising now with the rates as observed during the period of 1965–1980 (Kumar and Mittal 2006; Singh and Sidhu 2006; Dhillon et al. 2010). Moreover, excessive inputs of agrochemicals resulted in the increase in environmental pollution caused by increased availability of free and reactive chemical species (like nitrate, phosphate, ammonia, chloride and heavy metal contents) in the soil system (Shiva 1991; Singh 2001). The dooming effects of agro-chemicals on soil ecosystems can be easily seen in several regions in India, particularly in Haryana and Punjab states. Overall, green revolution led to a socio-economic disparity among the farmers by favouring agro-based industries, large landholding farmers and negatively influencing small landholding farmers on the one hand, and the environmental pollution, vulnerability of water resources, declining soil fertility and increased emissions of greenhouse gases (GHGs) on the other hand (Singh 2000). Therefore, the first and foremost challenge for the Indian agriculture is to feed the growing population (i.e. food security), followed by the judicious use of natural resources, by maintaining socio-economic balance (in the form of yield, market and livelihood) and incorporation of traditional knowledge and resource inputs (Fig. 2) (Kumari et al. 2019). These challenges are elaborated in the following sub-sections:

Food security

According to the recent estimate of United Nations, ~ 795 million people in the world were undernourished in 2014–2016 (Arulbalachandran et al. 2017). This figure was even higher earlier (i.e. 18.6% of total population during 1990–92) and has declined to 10.9% in 2014–16, which showed a reduction in the share of undernourished people in a growing global population. However, it is still being significantly higher and a massive number of people need an active, healthy and wealthy life (Arulbalachandran et al. 2017). Thus, the concept of food security which is based on food availability, accessibility, stability and its utilization (Schmidhuber and Tubiello 2007) came into the light. At the World Food Conference, 1974, the term "food security" was defined as the "availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices" (Souza and Rao 2016). On the contrary to food security, United States Department of Agriculture (USDA) defines food insecurity as a situation of "limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways" (Souza and Rao 2016). Thus, achieving food security in a sustainable way is the world's most imperative sociological, political, economic and scientific challenge of the twenty first century.

Food insecurity is majorly a problem for those countries having high fertility rates, and thus, rapid population growth enhancing the challenge of meeting their nutritional needs adequately (United Nations Development Programme, UNPD 2007). A remarkable increase (of ~ 145%) in world food production is observed since the introduction of green revolution (Pretty 2008). However, the issue of food security is still more pronounced in poor countries. According to an estimate (as in 2003), 2780 kcal day^{-1} is the average per capita global food requirement which is less than 2200 kcal day^{-1} for poor countries (Pretty et al. 2006). The population growth is relatively high in India with a current population of ~ 1.27 billion. India stands at the 74th position in the Food Security Index (Economic Intelligence Unit 2017). However, the growth of food production was found higher than the population growth for the past three decades (Sharma and Arora 2006). India ranked 103rd in the Global Hunger Index 2018 (https://www.globalhungerindex.org/results/). As per an estimate, there will be a requirement of ~ 122 MT of rice, 102 MT of wheat, 41 MT of course grains, 28 MT of pulses and 143 MT of milk to feed the 1.3

billon people in India by the year 2020 (Sharma and Arora 2006). Therefore, agriculture production needs to increase by almost twofolds (from 206 MT at present to 380 MT) per annum to feed a population of 1.4 billion by 2025 (Majumdar et al. 2014).

Water scarcity and salinization

Water is a prerequisite for the agricultural production. For example, to produce one ton of grain, ~ 1000 tons of water is required (Arulbalachandran et al. 2017). The predominant monsoon-dependency of Indian agriculture led it always to be at crossroads (Mall et al. 2006; Srivastava et al. 2016). Precipitation and water availability is an uncertain phenomenon in India as well as in most part of the world (Sarkar et al. 2017; Singh et al. 2017); therefore, crop water requirement is mainly fulfilled by supplemental irrigation such as canal and well irrigation (Chowdary et al. 2005). Agriculture consumes ~ 70% of global surface water for irrigation and crop production. A twofold increase in the cropland area under irrigation is observed in the past 50 years (Foley et al. 2011). Of the total global freshwater withdrawal, ~ 30% is used alone for rice cultivation (Ehrlich and Harte 2015). Further, more than 45% of total freshwater is consumed by flood-irrigated rice in Asian countries, which are two to three folds higher than that for maize and wheat like cereal crops (Singh 2013). Such resource-intensive agriculture enhances the crop yield by two- to threefolds. However, changing climate conditions impeded the continuous water availability in most countries of the world, which further impacted the sustenance of conventional irrigation practices (Du et al. 2015). Moreover, crop production is more influenced by water scarcity as compared to the land degradation, especially in areas having inadequate rainfall. Thus, maintenance of the continuous water availability seems to be the major challenge for the present agriculture in the near future (Millennium Ecosystem Assessment 2005; Pretty et al. 2010; Alrøe et al. 2016).

Agricultural demand of stored water (ground and surface water) for irrigation in India is already very high and it is expected to rise by 56% by 2050 (Kaur et al. 2013). India is the largest user (~ 230 km^3 $year^{-1}$) of groundwater in the world. Thus, water scarcity is expected to result in the food shortages, raising food prices and increase in the food imports by the resource poor countries (Arulbalachandran et al. 2017). In addition, injudicious use of water for irrigation or increase in water availability due to climate change phenomenon also intensified the process of soil salinization due to increased waterlogging (Kumar and Singh 2003; Wichelns and Oster 2006). Currently, waterlogging and soil salinization are affecting about 5.5 and 8.4 Mha areas in India, especially in Haryana state (Ritzema et al. 2008). Therefore, in addition to judicious use of water resources, proper irrigation water management also needs equal attention of the policy makers.

Soil quality deterioration

Soil is a viable system which faces the first and foremost consequences of agricultural practices (Singh et al. 2016a; Srivastava et al. 2015, 2016). Soil quality is the capacity of soil to interact with the ecosystem components for maintaining its physico-chemical environment, biological productivity and promoting the health of plants as well as animals (Doran and Parkin 1994). Soil organic carbon (SOC) is one of the important indicators of soil quality which controls many soil properties such as nutrient cycling, soil structure maintenance and pesticide and water retention (Sathya et al. 2016; Srivastava et al. 2016). During green revolution decades, injudicious application of agrochemicals led to an alarming situation for the soil system (Srivastava et al. 2016). Deterioration in soil organic matter (SOM) under intensive farming systems is the main cause of decline in soil quality (Sankar Ganesh et al. 2017). SOM plays a key role in long-term conservation of soil by regulating microbial activities as it provides substrates for the decomposition by the microbes (Abiven et al. 2009).

The amount of C stored in soils is estimated at ~ 3000 Pg (Jansson et al. 2010) which acts as a potential sink of atmospheric carbon dioxide (CO_2). Changes in SOC positively correlate with the soil biological indices such as microbial biomass and activity (Garcia et al. 1994). Based on mean annual rainfall, Indian agriculture can be categorised into five distinct bioclimatic regions with a spread over 160 Mha of land area (Bhattacharjee et al. 1982). The SOC levels in India vary in the range of 20–25 Gt C in the top 1 m (Sreenivas et al. 2016), which is equivalent to 4–8 g kg^{-1} SOC levels for most cultivable soils (Lal 2016; Pal et al. 2015). Thus, India contributes 1.4–1.8% (of 1408 Gt) of the global SOC stock in the top 1 m (Nath et al. 2018).

As per an estimate by Smil (2002), about 40% of the human population derived their food product using chemical fertilizers produced by the Haber–Bosch process. The world nitrogen fertiliser demand is increasing at an annual growth rate of 1.7% (FAO 2011). Of the global nitrogen fertilizer use, the Asian continent alone consumes 68% (FAO 2011). India and China alone share ~ 49% (25 and 24%, respectively) of the fertilizer consumption in Asia, majorly for wheat (18%), rice (16%) and maize (16%) crops (FAO 2011). Injudicious application of chemical fertiliser (and a subsequent reduction in organic manure inputs) is further enhancing the acidification of tropical soils which are already acidic by nature (Galloway et al. 2008). The soil acidification further leads to the degradation of soil quality and deterioration of soil productivity in the long term (Sankar Ganesh et al. 2017). Injudicious application of chemical fertilisers, soil nutrient mining and deficiencies and poor cropping practices led to the degradation of more than 60% of the agricultural land in India (ICAR 2010). Thus, sole application of chemical fertilisers in tropical agriculture hindered the yield of major food crops on the one hand and deteriorated soil biodiversity, fertility and nutrient-use-efficiency (NUE) on the other hand.

Nutrient availability

Fourteen elements are essential for proper plant growth and development, which are collectively called as nutrients (Sathya et al. 2016). Those elements needed in the higher amount are known as macronutrients whereas those needed in lesser amounts are known as micronutrients (Sankar Ganesh et al. 2017). Macronutrients are further divided into (1) structural nutrients, i.e., C, H, O; (2) primary nutrients, i.e., N, P, K and (3) secondary nutrients, i.e., S, Ca, Mg, whereas Fe, B, Cu, Cl, Mn, Mo, Zn and Ni come under the category of micronutrients (Sathya et al. 2016). Three primary nutrients present in the soil are most rapidly consumed by plants. Therefore, these three essential elements are externally supplied as commercial plant fertilizers, whereas biological nitrogen fixation (BNF), organic manures and plant residues constitute the other sources of nutrient supply (Sankar Ganesh et al. 2017). Like macronutrients, micronutrients are also essential for plant growth but comparatively in low amounts. Micronutrients such as Cu, Mn, Fe and Zn act as co-factor for several enzymes involved in the carbohydrates, proteins, lipids and nucleic acids' metabolism (Barker and Pilbeam 2015).

The nutrient concentration and their availability are the key factors for enhanced crop productivity (Kumar et al. 2015). For example, rice crop productivity is highly influenced by micronutrient availability (Zeng et al. 2011). Injudicious application of organic and inorganic agrochemicals accompanied by surface runoff and soil erosion are causing deficiency of major macro- and micronutrients (Bronick and Lal 2005; Wakeyo and Gardebroek 2017). The nutrient deficiency resulted in the retardation of various plant enzyme and/or protein functions, metabolic disturbances and cell damage which ultimately affect crop productivity (Gill and Tuteja 2010). Thus, nutrient availability is a major challenge in the present agriculture system. Nutrient, specifically micronutrient, mobility is governed by several factors like their concentration, operationally defined chemical fractions, organic matter, pH and soil–plant–microbe interactions (Shukla et al. 2015). Thus, it is imperative to improve NUE (capacity to utilize nutrients) by the judicious availability, nutrient cycling and utilization by the crop plants in an agro-ecosystem (Kumar et al. 2015) to improve crop growth and yields (Gourley et al. 1994). Thus, adapting improved agronomic management techniques, developing efficient crop varieties and promoting microflora-based agricultural practices are highly necessitated.

Socio-economic status of farmers and their landholdings

As per the Government of India (GOI 2014) report, the small and marginal landholding farmers (SLHs), dominated by Scheduled Castes and Scheduled Tribes (Dev 2012), account for ~ 85% (117 million out of 138 million) of total agricultural landholders. SLHs are cultivating over 72 Mha of land and contribute 50–60% of India's total food requirement (Nath et al. 2018). Moreover, rural women account for ~ 83% share in Indian agriculture majorly due to migration of men towards rural non-farm sectors (Nath et al. 2018). Moreover, their landholdings occupy the world's most ecologically and climatically vulnerable lands (IFAD 2012; GAP 2014). Thus, these farmers are the most susceptible group due to environmental degradation and continuously facing the challenges of hunger, poverty and further land degradation (Lal 2016). The shift of farmer's interests towards cultivation of cash crops (e.g., rubber, coconut and coffee), possibly due to weather instability and increased rate of meat consumption, is also threatening the long-term sustainability of Indian agriculture (Srivastava et al. 2016).

Overall, the challenges of food security, soil quality deterioration and farmers' socio-economic status altogether cannot be achieved judiciously by sole dependency on green revolution-based agriculture practices due to their various undesirable impacts (Fig. 3). It is evident from various studies conducted throughout the world that regardless of the remarkable increase in the grain production, several crops (e.g., wheat) have not yet attained their ecological yield in several countries (Lal 2007). Thus, there is a strong need of alternative technologies which should be based on traditional knowledge, low external inputs and ecologically-sound, for meeting these challenges (Srivastava et al. 2016). In the following sections, a brief insight has been given on different dimensions of emerging agricultural practices under the present climate change scenario for understanding the concept, need, challenges and opportunities for the sustainable agriculture.

Need for sustainability in agriculture

It is now established that green revolution-induced agrochemical inputs and cropping systems exaggeratedly affected the biodiversity and its interactions within soil (Mander et al. 1999). Thus, the existence of most of the soil microbial community, a major building block of soil ecosystem, has become marginalized (Pandey and Diwan 2018). As stated earlier, India is currently facing the twin challenges

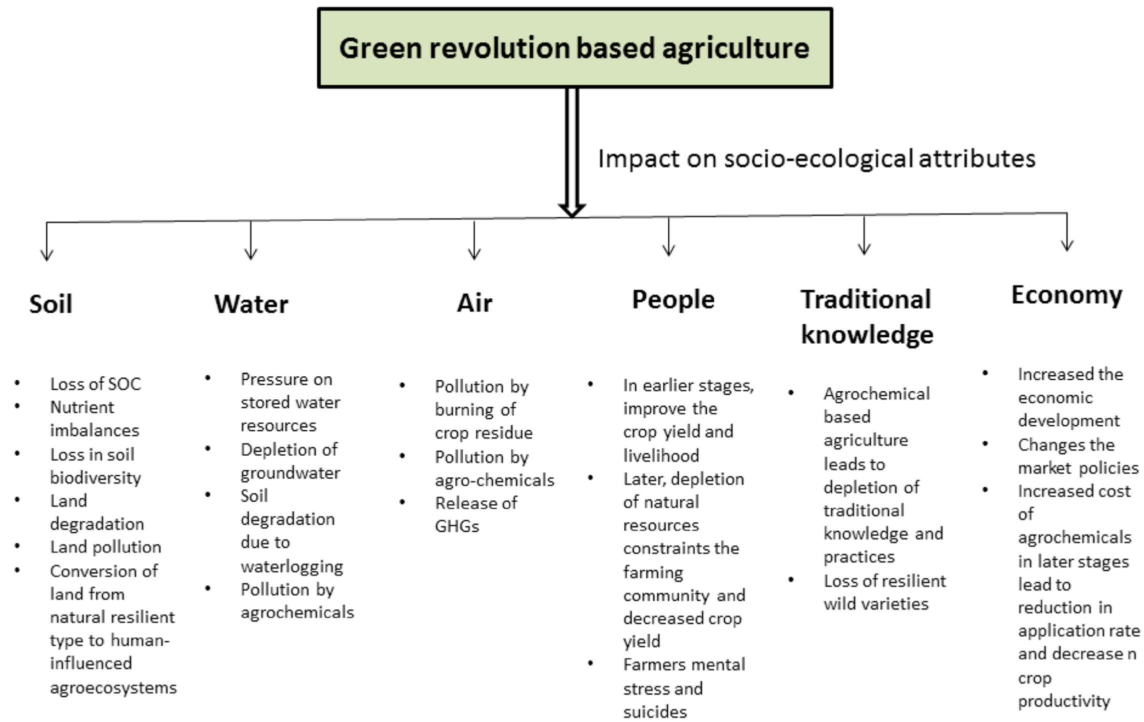

Fig. 3 Impact of green revolution-based agricultural intensification on different environmental components

of producing high food to meet the requirement of growing population and reducing the environmental footprint of agriculture (Godfray et al. 2010; Foley et al. 2011; Saikia et al. 2013; Srivastava et al. 2016). Adoption of green revolution improved the crop productivity initially till 2005; however, a stagnation and even reduction in yield is now reported in several regions of the world (Singh et al. 2016a; Srivastava et al. 2016). For example, 25–30% decline in rice and wheat grain yields was observed in the Philippines, India, Indonesia and Pakistan in the past 16 years, in spite of using recommended cultural practices (Pretty 1995). The initial increase in crop productivity indirectly resulted in the global reduction of 161 Gt C emissions till 2005 by reducing the conversion of marginal and vegetated land into agricultural land (Burney et al. 2010; Vermeulen et al. 2012). However, by the year 2016, 4.7% increase in India's GHG emissions was observed (http://www.climateactiontracker.org), of which agriculture sectors contributed ~ 17% (Nath et al. 2018). The increased emission from agricultural sector is catalysing the global warming and climate change phenomenon and expected to be severely affected by the climate change in the coming decades.

Previously, scientists' explored only one dimension of agriculture, i.e., as a production system; however, the negative environmental responses of that aspect led to have a deeper look on the other dimension of agriculture, i.e., as an ecological system (Ramakrishnan 2007). Recently the focus of the agriculture has been shifted from only maximizing the yield in short-term to the holistic management of the natural resource base for long-term productivity to achieve food security (Narwal 2010). Soil health (a continuous capacity to function as a vital living system) is one of the imperative components for long-term agricultural productivity (Sathya et al. 2016). This can only be possible by adapting efficient and harmless resource conservative practices like biofertilisers and organic matter inputs to the ecosystems (Fig. 4). Thus, to achieve the global population demand by maintaining long-term crop productivity and improving soil health, there is an urgent need of sustainable agriculture (Barea 2015).

According to Corwin et al. (1999) "the concept of sustainable agriculture is predicated on a delicate balance of maximizing crop productivity and maintaining economic stability, while minimizing the utilization of finite natural resources and detrimental environmental impacts." Tilman et al. (2002) define sustainable agriculture as "the practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered." It should integrate the sustainable agricultural practices along with a progressive co-ordination among the stakeholders using participatory learning and temporal adaptations (Srivastava et al. 2016). It should also add to the traditional ecological

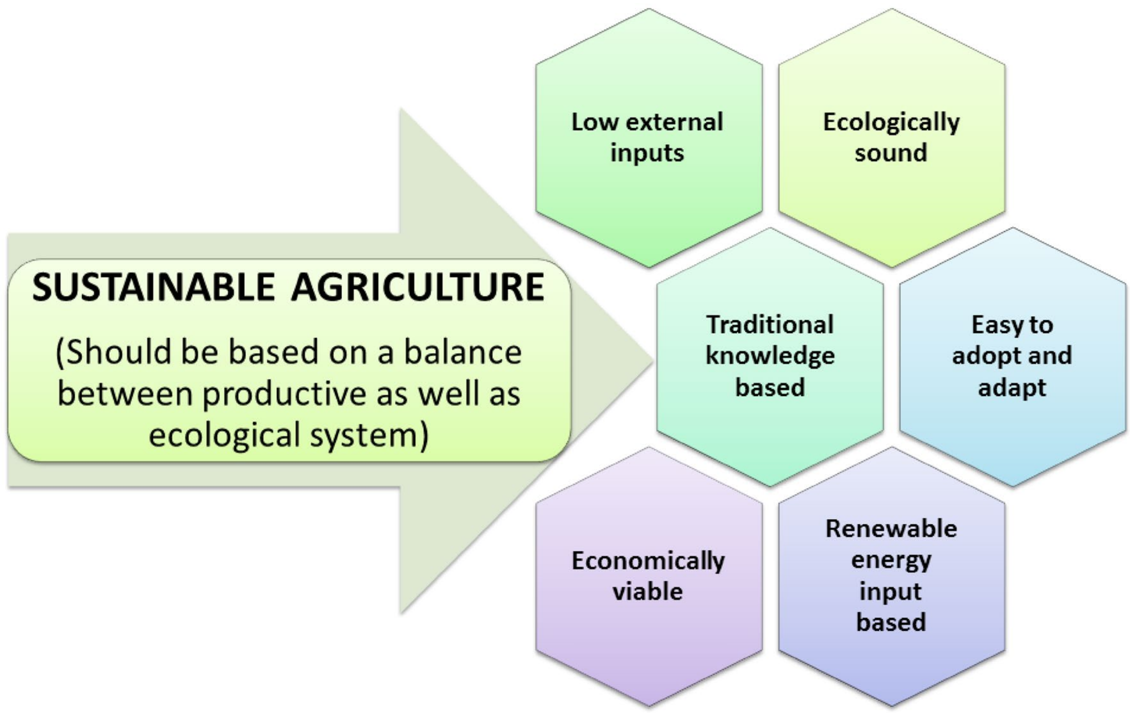

Fig. 4 Need and basis of the sustainable agriculture

knowledge to produce more by using less resource to feed the world population (Badgley et al. 2007). Thus, it can be stated that sustainable agriculture is multi-dimensional, which is based on three main pillars, i.e., social, environmental and economic sustainability (Clark and Dickson 2003) representing three P's framework of sustainable development goals i.e., People–Planet–Profit (Arulbalachandran et al. 2017). Therefore, the primary goals of sustainable agriculture should be (based on Lichtfouse et al. 2009) as follows: (1) promoting a prosperous social livelihood to the farming communities, (2) promoting environmental stewardship in terms of improved soil quality and reduced dependency on non-renewable resources with minimal damage to environmental resources, and (3) providing a more profitable farm income (Fig. 5).

Dimensions of sustainable agriculture

In the sustainable agriculture systems, integrated use of a wide range of soil, nutrients and pests management technologies (Pretty 1995) such as dung, crop residue and other bio-solids, BNF, mixed cropping, crop rotations, etc., has been promoted (Lal 2007; Narwal 2010). These measures led to improved soil quality and nutrient pools, biological diversity, climate resilience and ecosystem restoration by reducing soil degradation (Lal 2015), and also increasing socio-economic status of the farmers (Mtengeti et al. 2015). However, comparatively lower availability of organic and the subsidized rate of inorganic fertilizers is a major challenge for shifting towards sole organic management of agro-ecosystems (Huang et al. 2015; Solanki et al. 2015). Thus, the increased organic inputs to the soil along with a balanced application of inorganic fertilizers in the form of integrated nutrient management (INM) are being promoted in sustainable agriculture for enhancing soil quality and nutrient pools (Sanchez 2002). In a nutshell, the basic strategy for sustainability in agriculture lies in the fact that we need to produce more by using less environmental resources (Cassman et al. 2003). To achieve basic goals of sustainable agriculture, several new alternative practices such as conservation agriculture and organic farming for soil management, water saving agronomic practices, INM, biofertilisers, precision agriculture, etc. have been proposed and/or emerged (Mahajan and Gupta 2009; Singh et al. 2016a,b; Srivastava et al. 2016), which are elaborated in the following sub-sections:

Indigenous traditional knowledge

Indian agriculture, being a 10,000 years old practice, has emerged with inclusive traditional knowledge inputs throughout the development process (Borthakur and Singh 2013; Souza and Rao 2016). Indigenous Traditional Knowledge (ITK) is the knowledge acquired by the local people over a period of time by their real-time experiences through intimate interactions with the natural and physical

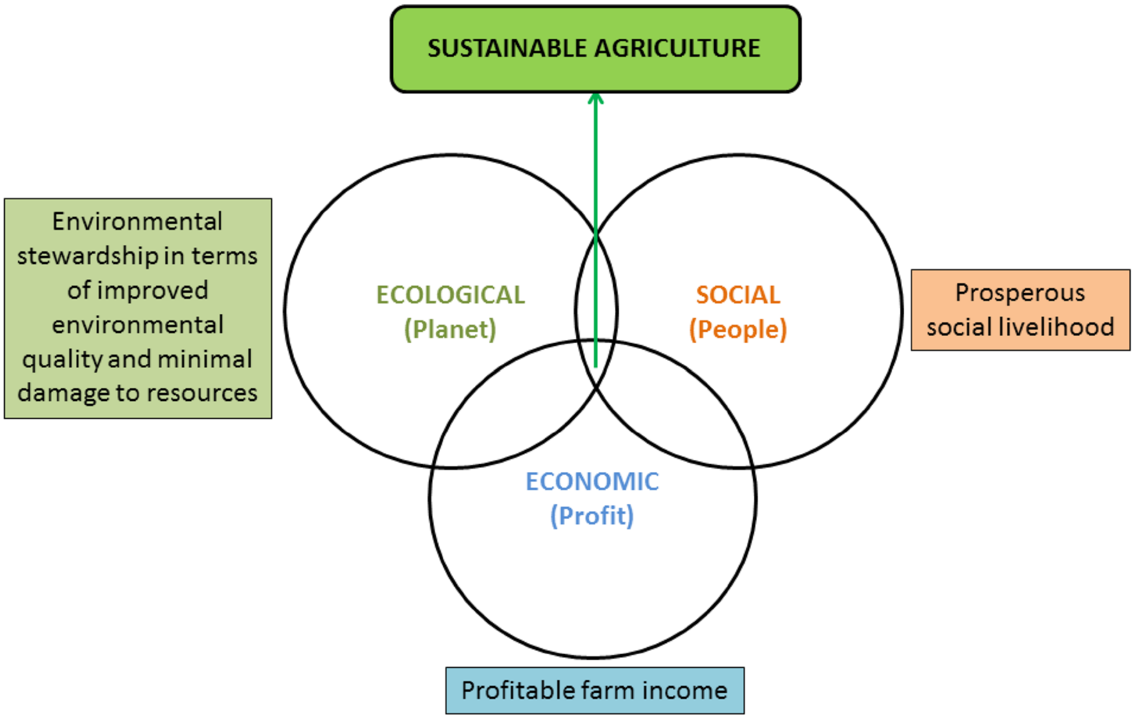

Fig. 5 Illustrative representation of the concept of sustainable agriculture

micro-environments (Kolawole 2001). ITK, being a scientific and sustainable knowledge base, is conveyed orally in several forms (e.g., stories, songs, beliefs, rituals, folklores, proverbs, cultural values, community laws, local language and agricultural practices) from generation to generation (Eagan and Dhandayuthapani 2019). It helps the rural communities for local-level decision making not only in agriculture but also in food preparation, education, health care and natural resource management (Warren 1993). ITK has immense potential for innovation due to their low cost, inherent dependency on local resources and less or non-polluting nature (Eagan and Dhandayuthapani 2019). The emerging technologies, consensus and approaches are now developed as a blend of the indigenous knowledge with modern agro-ecological scientific understanding to enhance the food security and environmental protection (Umarani and Subramaniyan 2000). This local microcosmic base of traditional agriculture offers a promising model for the sustainability in the agriculture. It could play a vital role in designing of the eco-friendly agricultural system as well as improving the livelihood of the rural population. Several examples stand for portraying the importance of indigenous techniques in the modern agriculture system. Some of the examples are outlined as (based on Somasundaram et al. 2015): crop rotation, companion crops, mixed crops, mulching, green manure, tank silt application, intercropping, cover crop, addition of organic pesticides like Panchagavya (derived from five cow products viz., milk, curd, ghee, urine and dung) and many others (see: Somasundaram et al. 2015 for more details). However, sole dependency on ITK will not help in meeting the food requirement of the population; thus, integration of modern technologies with ITK is needed for the agricultural sustainability (Sharma 2002).

Organic agriculture

Organic agriculture or farming is a form of sustainable agriculture which has potential to improve inherent soil quality by using traditional and extensive agricultural methods (Sankar Ganesh et al. 2017). It is based on the basic concept of increasing the role of microbial indigenous communities involved in various biogeochemical cycles in the natural ecosystem (Sathya et al. 2016). Organic agriculture has capacity to provide quality food without compromising the soil quality and health. Thus, organic agriculture is considered as one of the best agriculture alternatives for achieving agricultural sustainability (Ponisio et al. 2015). Its wider acceptance can be understood by the fact that more than 120 countries are practicing organic agriculture over 35 Mha of the agricultural land, globally (Mahapatra et al. 2009; Singh et al. 2016b).

Organic agriculture has potential to meet about 25–30% of nutrient needs of Indian agriculture, at present (Sankar Ganesh et al. 2017). At world level, India stands at 33rd and

88th positions, respectively, in terms of total land and proportion of land under organic cultivation to the total farming land area (Meena and Sharma 2015). Organic farming received wider attention in India during 2004–05 after the launch of National Project on Organic Farming (NPOF). At that time, it was practiced at 42,000 hectares which had increased by more than twofold (1.08 Mha) by 2010, leading India to stand as the second largest country in Asia for the area under organic cultivation (Meena and Sharma 2015; Singh et al. 2016b). To address the issue of sustaining crop yield by improving soil fertility and weed management via sustainable agricultural practices, the Government of India is now promoting organic farming methods derived from traditional farming practices like green manuring, weed management and biological pest control. Recently, Government of India held a high level parliamentary meeting under the chairmanship of Union Minister Dr. M.M. Joshi to discuss the present scenario of agriculture under the climate change conditions (https://thewire.in/agriculture/climate-change-agricultural-decline; accessed on 04.01.2019). The committee stressed on encouraging organic farming in India and also for developing policies for wider adoptability of organic agriculture under climate change scenario. Till date, nine Indian States have drafted policies for promoting organic farming and four states viz., Uttarakhand, Nagaland, Sikkim and Mizoram have been declared as 100% organic-based cultivation states (Meena and Sharma 2015).

In organic farming, reduced use of synthetic fertilizers invites the input of organics (e.g., green manure, farmyard manure, vermicompost, legume cover crops, peat moss, municipal biosolids, earthworm castings, bone meal, fish emulsion, poultry wastes and bat guano) as well as increased dependency on biologically originated materials like biofertilisers (Galvez et al. 2001; Kumar et al. 2015; Sankar Ganesh et al. 2017). Organic agriculture has already been established as a better alternative than chemical farming due to its positive consequences in terms of soil fertility, resource use efficiency, reduced environmental risks and traditional origin by involving local people benefits (Singh et al. 2016a, b; Srivastava et al. 2016). It can be better understood by the fact that the N supplied through FYM sustains more crop productivity than that supplied by chemical N fertilizers (Sankar Ganesh et al. 2017). Thus, to meet the crop N demand, in spite of higher application of chemical fertilizers like urea, various organic-N sources (mentioned above) are extensively being explored.

As stated previously, SOC, a dominant component of SOM, plays an important role in balancing the GHG emissions from agricultural sector. However, the organically managed systems showed comparatively higher GHG emission as compared to the conventional agriculture practices by enhancing the potential for soil C sequestration (Gattinger et al. 2012; Bhaduri et al. 2014; Chai et al. 2015). Greater organic matter build-up in organic fields helps to increase water holding capacity and reduce soil bulk density which leads to increase in the soil aggregate stability (Sihi et al. 2017). In addition, organic agriculture practices improve soil quality by enhancing mycorrhizal fungal association and propagules in the soil (Gryndler et al. 2005). In a nutshell, organic agriculture systems maintain the sustainable crop production by reducing dependency on agrochemicals and encourage the resiliency of soil system for the long-term production capacity (Grinsven et al. 2015). However, availability of organic manure could be a major constraint for the sole organic agriculture. As per an estimate of Govt. of India (GOI 2016), ~ 3000 Tg of manure could be produced annually by over 500 million livestock population of the country (Nath et al. 2018). Moreover, in spite of several ecological benefits of organic agriculture, a recent study by Searchinger et al. (2018) highlighted some inconvenient truths about the organic agriculture related with higher GHG emissions from organically amended soil systems as compared to the chemical fertilizer applied soils. However, it needs further assessment, and the relative GHG emissions in relation to SOC sequestration in soil should be evaluated for any conclusive results (Srivastava et al. 2018). Overall, the debate is still going on to adapt or not to adapt the sole organic agriculture system globally and the present consensus is lying on to judicious use of chemical and inorganic fertilizers in addition to various other emerging soil ameliorants (Singh et al. 2019a).

Soil microbes as a tool for sustainable agriculture

Soil microbes are an essential and integral part of living soil system which play a vital role in regulating many important components like nutrient cycling (mobilisation and uptake of major nutrients), soil fertility, soil biodiversity and plant health (Prakash et al. 2015; Sathya et al. 2016). Soil microbial community structure and functions are very sensitive to background conditions, and thus, serve as a better indicator of the status of soil health and soil nutrient pool as compared to the non-living indicators (Prakash et al. 2015; Sathya et al. 2016). For example, soil biochemical properties (e.g., enzyme activities) act as quick indicators of soil quality (Sihi et al. 2017) as they are involved in catalysing various reactions involved in nutrient cycling, provide positive feedback to the plant–microbe interactions in the rhizosphere and showed prompt responses to the environmental perturbations (Bhaduri et al. 2015).

Some of the most important functions of microbes for promoting plant growth and protecting soil health include nitrogen fixation, denitrification, phosphate and sulphate solubilisation, siderophore production, plant growth promotion, immune modulation, pathogen control and signal transduction (Prakash et al. 2015). Based on their availability and functions, soil microbes have been classified as follows: plant growth promoting microorganisms (PGPM) such as phosphorus solubilising bacteria (PSB) and potassium solubilising bacteria (KSB), endophytic microbes (residing in internal tissues of plants), vesicular–arbuscular mycorrhiza (VAM) and BNF (Kumar et al. 2015; Jaiswal et al. 2016; Sharma et al. 2016; Suman et al. 2016). Most of the microbes responsible for plant growth promotion belong to the endophytic microbial group which has ability to enter the host plants through wounds or root hairs present at epidermal conjunctions (Suman et al. 2016). In the following sub-sections, soil microbial role has been discussed in two parts, i.e., as biofertilisers and as BNF agents in terms of their role in sustainable agriculture.

Biofertilisers

Extensive application of N- and P-based fertilizers created a potential deficiency of K availability in soil system which can either be fulfilled by addition of K-fertilisers or by some other sustainable manner (Jaiswal et al. 2016). A range of microorganisms with their multifaceted positive effects on the plants have been found in the rhizospheric zone, collectively known as plant growth-promoting rhizobacteria or microorganisms (PGPR or PGPM). Somers et al. (2004) classified the rhizospheric microbes into four major categories based on their plant growth-promoting traits as follows: (1) biofertilisers (improves the nutrient uptake to the plant), (2) phytostimulators (increase the plant growth by producing phytohormones), (3) rhizoremediators (degrade organic pollutants), and (4) biopesticides (control diseases through antagonistic activity by the production of antibiotics, antifungal metabolites and synthesis of extracellular enzymes).

Potassium is found in several forms in the soil and a major part remains unavailable to the plants. A major group of microorganisms have been identified which have capacity to solubilise unavailable forms of K (such as minerals like micas, illite, and orthoclases) to the plant-available forms by releasing several organic acids. K-solubilising microorganisms are one of the best sustainable technologies, which solubilise the fixed form of K available for plant uptake (Jaiswal et al. 2016). PGPM have been reported to colonise roots of higher plants and help in nutrient acquisition (N, P and essential nutrients) or modify root architecture by phytohormone production to improve plant growth (Sharma et al. 2016). Moreover, PGPM helps in releasing monobasic ($H_2PO_4^-$) and dibasic ($H_2PO_4^{2-}$) forms of P to the rhizosphere which can be easily absorbed by the plants (Bhattacharyya and Jha 2012). They help in promoting plant growth and enhancing the availability of key nutrients such as SOC (by 17–39%), N (by 8–82%) and P (by 13–44%) in the rhizosphere (Kumar et al. 2015; Sathya et al. 2016).

Some examples of PGDM include the following: (1) bacteria: *Pseudomonas* spp., *Bacillus edaphicus*, *B. mucilaginosus*, *B. megaterium, Acidithiobacillus ferrooxidans* and some strains of *Achromobacter*, *Pisolithus*, *Cenococcum*, *Piloderma*, *Paenibacillus*, *Burkholderia*, *Aspergillus, Enterobacter, Herbaspirillum, Pantoea, Rhizobium*, *Streptomyces* and *Clostridium*; (2) fungi: *Aspergillus, Penicillium* and *Trichoderma*; and (3) *Streptomyces* and *Nocardia* (actinomycetes) (Mittal et al. 2008; Sheng et al. 2008; Tallapragada and Seshachala 2012; Meena et al. 2014; Zhang and Kong 2014). In addition to bacteria and fungi, a number of symbiotic associations of VAM with more than 90% plant species through external hyphae have been reported (Sharma et al. 2016). VAM associates with the plants for their C requirements and improves the fitness of host plant by scavenging minerals (macro- and micronutrients) in the agro-ecosystems (Atkinson et al. 2002; Brundrett 2002; Abo-Rekab et al. 2010). These fungal associations account for 50% of soil microbial biomass in agricultural soils (Olsson et al. 1999). Some major benefits of AM fungi to the crop plants include the following: improved nutrient uptake and cycling, nutrient transfer in intercropping systems, plant tolerance to biotic and abiotic stresses and interaction with other soil organisms (Priyadharsini and Muthukumar 2015).

Biological nitrogen fixation

Nitrogen (N), an essential element for all life forms, is required in large quantities for the synthesis of amino acids and nucleotides (Sathya et al. 2016). It can either be supplied as natural sources or through chemical fertilizers. As per a global estimate, only 33% fertilizer N is utilised by plants for various functions whereas 67% is usually converted to the non-reactive atmospheric N_2 (Vitousek et al. 1997). Therefore, to improve the nitrogen use efficiency and reduce the ill-effects of chemical N in the environment, natural fixation processes like BNF are now getting greater importance in the sustainable agriculture policies. Symbiotic or biological N-fixation constitutes the most important natural source of N supply to the plants. BNF through legume crops is the imperative source of crop nutrition. BNF accounts for ~65% of N currently used in agriculture (Thamdrup 2012).

Use of legumes either as green manure, forage or for grains in crop rotation helps in BNF, restoring SOM level in soil and reducing pest and disease problems by their allelopathic behaviour (Narwal 2010). The legume–rhizobial symbiosis fixes 13–360 kg N ha^{-1} (Bohlool et al. 1992) which considerably reduces the chemical fertiliser N requirement (Bhattacharyya and Jha 2012). The total contribution of legume crops in India amounts to 2.24 Tg N $year^{-1}$ (Rao and Balachandar 2017). Further, several crops like rice, wheat and sugarcane also have capacity to fix N without forming symbiotic relationships (Sathya et al. 2016). These crops form association with free living diazotrophs and can fix 10–160 kg N ha^{-1} (Bohlool et al. 1992). Moreover, many cyanobacterial species have the inherent potential to fix atmospheric N, especially in the rice crop (Song et al. 2005) and thus, improve soil fertility and crop production. Cyanobacteria have filamentous structure which helps in retaining soil moisture and improves soil physical structure (Kumar et al. 2015). It produces mucilaginous substances and several other metabolites like vitamins, amino acids, phytohormones, phenolics and flavonoids (Kumar et al. 2015). Moreover, the heavy organic biomass of cyanobacteria after decomposition led to substantial increase in SOM level as well as N and P sequestration (Saadatnia and Riahi 2009). Moreover, a small fern called Azolla (*Anabena azollae*) has significant potential (~ 120 kg N ha^{-1}) to fix N in paddy field (Kohli and Mitra 1987). It further has capacity to fix up to 400 kg N ha^{-1} which is considerably higher than that fixed by legumes (Narwal 2010). Therefore, it has tremendous potential to reduce the inorganic fertilizer N demand and improve soil health, if used properly. Though the global N inputs to the crops through eco-friendly BNF amounts to 55–60 Tg $year^{-1}$, it is comparatively less than the actual N requirements (Rao and Balachandar 2017). BNF accounts for a greater contribution (~ 11% of world contribution) in Indian agriculture by producing 5.20–5.76 Tg N $year^{-1}$, of respective cereal crop and legume shares of 32 and 43% (Rao and Balachandar 2017).

Resource efficient agronomic practices

To manage the different components of agricultural sustainability, several agronomic practices have been developed with the basic focus of enhancing resource use efficiency and reducing the GHG emissions and soil quality deterioration. Some of the resource efficient emergent agronomic practices are described in the following sub-sections:

System of rice intensification (SRI)

Rice is a water-intensive crop grown on a major part of India. Under the present situation of water scarcity, conservation of irrigation water is more imperative. Nowadays, several management practices such as aerobic rice cultivation, dry seeded rice and system of rice intensification (SRI) for growing rice under non-puddled conditions have emerged for reducing the rice water requirement and GHG emissions without compromising crop yields (Stoop et al. 2002; Senthilkumar et al. 2008; also see: http://sri.ciifad.cornell.edu/). Of various methods that have emerged recently, SRI gains wider attention of the farming community, globally. SRI includes the basic principle of feeding the soil with chemical and/or compost fertilisers to feed the plants in response which ultimately resulted in the increase in crop productivity (Mishra et al. 2007, 2013). SRI is based on a package of modified resource conserving agricultural practices which include: (1) transplanting young seedlings for avoiding transplantation shock, (2) 1–2 seedlings per hill to avoid competition at the early growth stages, (3) wider plant spacing with increased inputs of organic fertilizers for avoiding resource competition and providing sustained nutrient supply to the young seedlings, and (4) maintaining the soil moist but in aerobic conditions (not puddled anaerobic condition) to reduce CH_4 release and conserve water loss from seepage and evaporation (Stoop et al. 2002; Uphoff et al. 2011). The basic conditions applied in SRI contribute to reducing seed requirement, increased productive tiller number, healthier roots, less dependency on mineral fertilisers and irrigation water and comparatively more yield per unit area even under drought year (Balamatti and Uphoff 2017). SRI was first introduced in India in 2008 (in the Dharwad district of Karnataka), for improving the sustainability of rainfed rice cultivation. Studies conducted on SRI suggested that it was readily welcomed by those farmers facing the problem of water scarcity and resource limitations, especially SLHs (Balamatti and Uphoff 2017). Thus, SRI is helping the resource-poor farmers to increase their livelihood and economic returns in addition to environmental conservation. A study suggests that over 29,000 farmers had adopted SRI practices in the Dharwad and neighbouring districts of Karnataka in less than 6 years. These results revealed the wider adaptation of SRI in India (Balamatti and Uphoff 2017). However, it is still awaiting its establishment and adaptation by large landholding farmers having intensive and modern resource bases.

Conservation agriculture

Tillage modifies all the attributes of soil environment (Galvez et al. 2001; Neelam et al. 2010). Soil disturbance by tillage is regarded as the primary cause of the SOC loss (Luo et al. 2010). Moreover, the disturbance created by tillage leads to increase in water demand as well as GHG emissions and deteriorates soil quality. Further, removal of crop residues for livestock fodder or biofuel production can threaten environmental quality and food security (Wolf et al. 2003; Lal 2005). Therefore, measures have been proposed to reduce or avoid tillage and conserve residues in situ for crop production and soil quality improvement. Conservation agriculture is one of the well-known sustainable ways of agriculture (Hobbs et al. 2008) which fulfils these ill-effects in an appropriate manner (Abrol and Sangar 2006). It is based on three principles viz., (1) minimal soil disturbance, (2) residue retention or mulching, and (3) sustained nutrient and weed management by crop rotation and cover crops (Paul et al. 2013).

In India, the first principle of conservation agriculture, i.e., no tillage (NT), is majorly accepted and adapted in the widely practiced rice–wheat system of the Indo-Gangetic plains (Bhan and Behera 2014). The basic reason underlying this acceptance includes the instant economic benefits of zero tillage technology to the farmers. Moreover, NT practices are less energy intensive, help in maintaining soil aggregate stability and enhance SOM build-up in agro-ecosystems and thus, improve resource use efficiency and soil fertility. More than 1.5 Mha area in India is currently under conservation agriculture system (Jat et al. 2012). Shifting from conventional tillage to conservation tillage has been reported to reduce GHGs emission (Mishra et al. 2013), water requirement for irrigation and conservation of fungal hyphae for better nutrient utilization and conservation. For example, some studies performed in the north eastern India showed that NT practice can increase SOC level by 71%, whereas biological activity and yields by 47 and 49%, respectively, as compared to the conventional tillage in rice-based cropping system (Ghosh et al. 2010). Moreover, a reduction of 18.63 kg ha^{-1} in CO_2 emission and 126.75 m^3 ha^{-1} in irrigation water use was reported from wheat cropping system in India (Singh et al. 2016b). In addition to reducing CO_2 emission by increasing SOC level in soil, conservation agriculture practices (viz., residue retention) also help in reducing crop residue burning, thus decreasing the release of photosynthetically trapped atmospheric CO_2 from the soil system. However, the sustainability analysis of residue retention and its wider adaptation is occasionally bargained by several other measures, which is a matter of concern for the agricultural sustainability.

Water saving techniques

Water resources are limited and currently facing multiple pressures under climate change conditions. Paddy and wheat crops are two water intensive crops with respective water use of 62 and 20% of total irrigation water applied; therefore, most of the strategies belong to the water conservation from paddy fields (Kaur et al. 2013). In India, especially in the Punjab and Haryana, various measures have been taken in to consideration for developing suitable adaptation strategies for sustainable water (especially groundwater) use. Kaur et al. (2013) extensively reviewed the water saving strategies applied in India and outlined following techniques: improvement in irrigation efficiencies, reduction in application losses, use of laser levelling technology, shifting transplanting time of rice, improved irrigation methods, crop diversification, recharge through drains using check structures, renovation of village ponds, roof top rainwater harvesting, wastewater recycling and water reuse (see: Kaur et al. 2013). In addition, several agronomic practices applied in modern agriculture are also based on reduced application of water for crop production. Researches are being carried out extensively to reduce water loss and increase water use efficiency by crop plants, in recent years.

Soil amendments

In addition to compost and vermicompost application to the soil under organic agriculture system, several other soil ameliorants are now added to the soil for restoring soil health and improving soil quality by enhancing SOM pool. Some of the amendments include the incorporation of biochar derived from lignocellulosic biomass, fly ash, sewage sludge and municipal solid wastes (Singh et al. 2016a). These amendments are either applied in the conventional practices or along with some recently adopted sustainable agricultural practices. Biochar amendment to soil has shown multifaceted applications in sustainable agriculture (see: Singh et al. 2015a), depending on the basic soil properties. Integration of biochar, a potential soil C sequestration agent, in conservation agriculture practices has been reported to show synergistic effects for enhancing SOC level, improving soil fertility and mitigating climate change (Singh et al. 2015b). However, several agronomic benefits and environmental risks associated with biochar application to the agroecosystems depend on soil properties (Kuppusamy et al. 2016; Singh et al. 2019b). Similarly, other soil ameliorants have also been proved to improve soil properties and crop yield, though they also have certain risks which need to be rectified before wider application. However, elaborate studies identifying the role and effect of various soil ameliorants in Indian agricultural fields still need substantial research.

Nano-technology

To feed the mammoth population of India, resource conservation and precision agriculture, adoption of new technologies is also needed (Agarwal et al. 2015). Nanotechnology, with its novel and precise approaches, presents a prompt alternative for these aspects, if used wisely. It offers enormous opportunities for providing better solutions to the multiple problems in agriculture. Nanotechnology-based measures and devices viz., nano-fertilizers, nanosensors, nanopesticides and nanoformulations as biocontrol agents, are being explored for precision agriculture, early detection of contaminants, natural resource management, efficient delivery of agrochemicals and enhanced ability of nutrient absorption by plants (Baruah and Dutta 2009), in addition to application in plant breeding and genetic transformation (Torney et al. 2007). It assists in making agriculture proficient and resourceful, which further help in meeting the demand of food supply and safeguarding environmental sustainability (Nair et al. 2010). Various soil physico-chemical properties like soil texture, SOM content, pH and cation exchange capacity majorly regulate the sorption, mobility and transport of nanoparticles in the soil (Benoit et al. 2013). Studies reported positive impact of nanoparticles on seed germination, growth and vigour index of several crop plants (Singh et al. 2016c). Further, studies on the interaction of nanoparticles with plants, microorganisms and soil are available (Bakshi et al. 2014; Mohanty et al. 2014); however, their impact on soil biota still needs more attention of the scientific communities. Thus, for wider application of nanotechnology, the fate, transport, bioavailability and consequent toxicity of nanoparticles need to be extensively explored under different soil conditions (Benoit et al. 2013). Overall, the basic resource utilisation mechanism applied under sustainable agriculture practices is illustratively presented in Fig. 6.

Agricultural sustainability under climate change conditions

Increasing concentration of GHGs in the atmosphere is regarded as the major anthropogenic cause for climate change due to global warming phenomenon. Agricultural activities contribute 10–12% of total GHG emission, globally (FAO 2015), whereas this figure is quite higher (i.e., 19%) in India (Sharma et al. 2011). Reduction of GHG emissions by reducing the causes of emissions such as fertiliser application and tillage applied in conventional agricultural sectors may compromise the food security by reduction in yield. Further, climate change may regulate the major dimensions of food security by severely affecting the future agricultural productivity (Mall et al. 2006; Schmidhuber and Tubiello 2007; World Bank 2008; Godfray et al. 2010). Under climate change scenarios, changes in temperature and precipitation pattern and intensity (via increased extreme events and spatio-temporal shifts), soil degradation as well as pest and pathogen behaviour imposed serious pressures on conventional agricultural systems, globally (Schmidhuber and Tubiello 2007; Calzadilla et al. 2013). It is well known that soil acts as a buffer by mediating soil microbial activities which resulted in the increased CO_2 (a major greenhouse gas) fluxes. Thus, improved soil buffering capacity would help in mitigating the impact of climate change on the agricultural productivity. In regard to the projected climate change, agriculture needs to be progressive for adaptation by recommending changes in agricultural practices by inculcating traditional knowledge with modern technologies (Eitzinger et al. 2009).

Over the past 50 years (from 1960 to 2010), GHG emissions have increased by 161% (14.81–38.71 Tg C_{eq} year^{-1}) from the agriculture sectors majorly due to increase in inputs like chemical fertilisers, change in cropping pattern (monotypic monoculture cropping) and mechanisation of agriculture (Sah and Devakumar 2018).

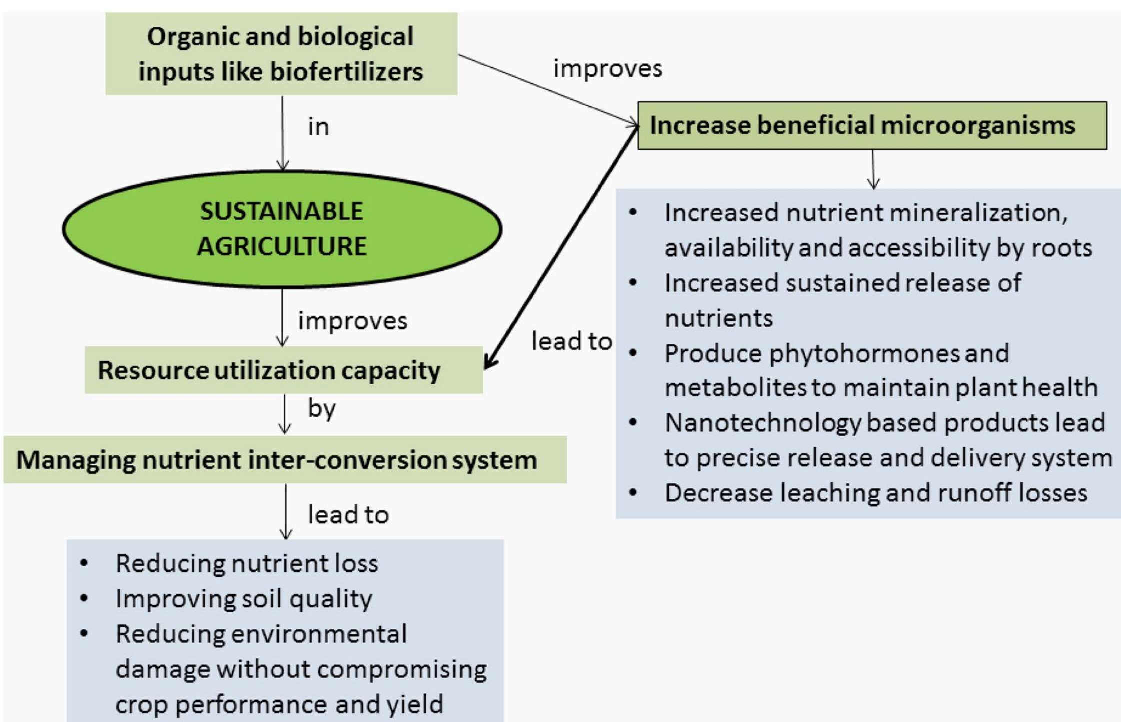

Fig. 6 Resource utilization mechanism for sustainable agriculture system

Among crops, maximum GHG emission (23.75 Tg C_{eq} ha^{-1}) is recorded from rice crop (Sah and Devakumar 2018). Moreover, inorganic nitrogen fertiliser inputs are responsible for highest proportion of emissions among the agricultural inputs used, globally (Cheng et al. 2011; Yan et al. 2015). Though the land use change and fertiliser inputs increased the overall GHG (especially CO_2 and N_2O) emissions in the recent past, a substantial decline in CH_4 emission from Indian soils is reported due to comparatively lower SOC content and reduction in anaerobic environment for the paddy crops in the country (Mitra 1992). Climate change is expected to have more severe impacts in India where ~ 45% population is relying on agricultural activities for their livelihood. There is an increase of 0.60 °C in mean annual temperature recorded in India over the past 100 years (Arora and Bhatt 2016). Based on the climatic conditions and crops grown, India is divided into 20 agro-climatic zones (Sah and Devakumar 2018). Of different zones, 75% cultivated land comes under arid and semiarid regions (INECC 2010). Thus, Indian agriculture seems highly vulnerable under climate change conditions. Reduction in productivity of the food crops as well as an expected land scarcity under the climate change scenario is foreseen by 2050 (Nelson et al. 2010). According to an estimate, climate change is expected to decline 4, 6 and 18% yields of irrigated rice, rain-fed rice and late-sown wheat crops by 2020 in India (Arora and Bhatt 2016).

Climate change is expected to have severe impacts on the water resources, coastal zones, agriculture, human health, food security, ecosystems and biodiversity. Due to climate change, a decline in crop yield up to 30% is predicted in Central and South Asia (Arora and Bhatt 2016). The sustainable agriculture is expected to cope-up with the severe impacts of climate change due to their inherent capacity to develop ecosystem resilience, resource conservative nature and dependency on more biological or natural measures. Moreover, fossil-fuel based mechanization in agriculture is also one of the major contributors to GHGs emissions from the agricultural sector. Promoting the use of renewable resources such as solar, biomass and biofuels, wind, geo-thermal, small-scale hydro-, tidal- and wave-generated power would help in reducing environmental damage and GHG emissions (Chel and Kaushik 2011). Government may play a central role in promoting the use of renewable energy technologies for agricultural activities by providing subsidies to the farmers. Overall, sustainable agricultural practices have been developed and combined with various inherent measures to cope up to some extent with the adverse impacts of climate change without compromising the food security for the coming generations.

Future developments and concluding remarks for agricultural sustainability

Several resilient varieties are being developed by using plant breeding and other biotechnological measures. Such innovation should be further carried out for other food crops. Introduction of mixed cropping and wisely managed crop rotation is also needed. Introduction as well as subsidized availability of renewable resources (e.g., electrification) in agriculture sector may help in further reducing environmental problems of a country. Development in the field of precision agriculture can be beneficial in terms of managing agricultural sustainability under climate change conditions. Research in the field of proper characterization and effects over various physico-chemical soil properties after soil amendments needs to be carried out further in India. A threshold dose for organic, inorganic, nanomaterials and biological agents in soil needs to be identified for different soil types to avoid negative impacts of these inputs. Further promotion of SLHs by providing some subsidies in terms of local carbon credit (based on SOC sequestration potential) can also be introduced for increasing the potential of soil C sequestration by these marginalized farmers.

Overall, this review provides a thorough understanding of green revolution and its impact on the socio-economic and environmental components. Challenges to the modern agriculture such as food security, soil quality deterioration, resource limitation and nutrient imbalances have also been explored. Agriculture based on higher natural and biological on-farm based inputs for improving soil microcosm to environmental macrocosm by the people for the long-term benefits for the people can be called as sustainable agriculture. It is the urgent need of the hour for managing the people–plant–profit aspects in a single goal. The present scenario showed a win–win approach for the initial phase of sustainable agriculture. However, for long-term sustainability, the wider spread and adaptation of various sustainable agriculture practices by all the pillars of a society is needed. The change in the mind-set of people from considering agriculture as an economic system to ecological system is the major challenge. Proper integration of modern agricultural practices and adaptation by the farming communities should be assured in the near future. The severe impacts of climate change cannot be ignored in the coming decades. Therefore, policies and practices need to be developed for shielding the farming communities, especially small landholders, from the instant losses by the extreme events.

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References

Abiven S, Menassero S, Chenu C (2009) The effect of organic inputs over time on soil aggregate stability—a literature analysis. Soil Biol Biochem 41:1–12

Abo-Rekab ZA, Darwesh RSS, Hassan N (2010) Effect of arbuscular mycorrhizal fungi, NPK complete fertilizers on growth and concentration nutrients of acclimatized date palm plantlets. Mesopot J Agric 38:9–19

Abrol IP, Sangar S (2006) Sustaining Indian agriculture—conservation agriculturethe way forward. Curr Sci 91:1020–1025

Agarwal A, Prajapati R, Singh OP, Raza SK, Thakur LK (2015) Pesticide residue in water—a challenging task in India. Environ Monit Assess 54:187

Alrøe HF, Moller H, Læssøe J, Noe E (2016) Opportunities and challenges for multicriteria assessment of food system sustainability. Ecol Soc. https://doi.org/10.5751/ES-08394-210138

Arora S, Bhatt R (2016) Resource conservation technologies (RCTs) for climate-resilient agriculture in the foothill of Northwest Himalayas. Conservation agriculture. Springer, Singapore, pp 71–111

Arulbalachandran D, Mullainathan L, Latha S (2017) Food Security and sustainable agriculture. Sustainable agriculture towards food security. Springer, Singapore, pp 3–13

Atkinson D, Baddely JA, Goicoechea N, Green J, Sanchez-Diaz M, Watson CA (2002) Arbuscular mycorrhizal fungi in low input agriculture. In: Gianinazzi SH, Schüepp JM, Haselwandtler K (eds) Mycorrhizal technology in agriculture: from genes to bioproducts. Birkhauser, Berlin, pp 211–222

Badgley C, Moghtader J, Quintero E, Zakem E, Chappell MJ, Aviles-Vazquez K, Samulon A, Perfecto I (2007) Organic agriculture and the global food supply. Renew Agric Food Syst 22:86–108

Bakshi M, Singh HB, Abhilash PC (2014) The unseen impact of nanoparticles: more or less? Curr Sci 106:350–352

Balamatti A, Uphoff N (2017) Experience with the system of rice intensification for sustainable rainfed paddy farming systems in India. Agroecol Sustain Food Syst 41:573–587

Barea JM (2015) Future challenges and perspectives for applying microbial biotechnology in sustainable agriculture based on a better understanding of plant-microbiome interactions. J Soil Sci Plant Nutr 15:261–282

Barker AV, Pilbeam DJ (2015) Handbook of plant nutrition. CRC, Boca Raton

Baruah S, Dutta J (2009) Nanotechnology applications in pollution sensing and degradation in agriculture: a review. Environ Chem Lett 7:191–204. https://doi.org/10.1007/s10311-009-0228-8

Benoit R, Wilkinson KJ, Sauve S (2013) Partitioning of silver and chemical speciation of free Ag in soils amended with nanoparticles. Chem Cent J 7:75

Bhaduri D, Purakayastha TJ, Patra AK, Singh M, Sarkar S (2014) Combined effect of tillage-water-nutrient management under rice-wheat agro-ecosystem: a study on chemical indicators of soil quality. Agrochimica 58:63–76

Bhaduri D, Pal S, Purakayastha TJ, Chakraborty K, Yadav RS, Akhtar MS (2015) Soil quality and plant-microbe interactions in the rhizosphere. In: Lichtfouse E (ed) Sustainable agriculture reviews. Springer, Heidelberg, pp 307–335

Bhan S, Behera UK (2014) Conservation agriculture in India—problems, prospects and policy issues. Int Soil Water Conserv Res 2:1–12

Bhattacharjee JC, Roychaudhury C, Landey RJ, Pandey S (1982) Bioclimatic analysis of India. NBSSLUP Bulletin 7, National Bureau of Soil Survey and Land Use Planning (ICAR), Nagpur, India, p21 + map

Bhattacharyya PN, Jha DK (2012) Plant growth promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Bohlool BB, Ladha JK, Garrity DP, George T (1992) Biological nitrogen fixation for sustainable agriculture: a perspective. Plant Soil 141:1–11

Borthakur A, Singh P (2013) History of agricultural research in India. Curr Sci 105:587–593

Bose B, Mondal S (2013) Climate change and sustainable agriculture in context to seed priming and role of nitrate. Vegetos nt J Plant Res 26:192–204

Brevik EC (2013) Soils and human health—an overview. In: Brevik EC, Burgess LC, Raton B (eds) Soils and human health. CRC, Boca Raton, pp 29–56

Bronick CJ, Lal R (2005) Soil structure and management: a review. Geoderma 124:3–22

Brundrett MC (2002) Coevolution of roots and mycorrhizas of land plants. New Phytol 154:275–304

Burney JA, Davis SJ, Lobell DB (2010) Greenhouse gas mitigation by agricultural intensification. Proc Nat Acad Sci USA 107:12052–12057. https://doi.org/10.1073/pnas.0914216107

Calzadilla A, Rehdanz K, Betts R, Falloon P, Wiltshire A, Tol RSJ (2013) Climate change impacts on global agriculture. Clim Change 120:357–374. https://doi.org/10.1007/s10584-013-0822-4

Cassman KG, Doebermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environment quality. Ann Rev Environ Resour 28:315–358

Chai Y, Ma S, Zeng XES, Che Z, Li L, Duan R, Su S (2015) Long-term fertilization effects on soil organic carbon stocks in the irrigated desert soil of NW China. J Plant Nutr Soil Sci 178:622–630

Chel A, Kaushik G (2011) Renewable energy for sustainable agriculture. Agron Sust Develop 31:91–118

Cheng K, Pan G, Smith P et al (2011) Carbon footprint of China's crop production—an estimation using agro-statistics data over 1993–2007. Agric Ecosyst Environ 142:231–237

Chowdary VM, Rao NH, Sarma PBS (2005) Decision support framework for assessment of non-point-source pollution of groundwater in large irrigation projects. Agric Water Manage 75:194–225

Clark WC, Dickson NM (2003) Sustainability science, the emerging research program. Proc Natl Acad Sci USA 100:8059–8061

Corwin DL, Loague K, Ellsworth TR (1999) Assessing non-point source pollution in the vadose zone with advanced information technologies. In: Corwin DL, Loague K, Ellsworth TR (eds) Assessment of non-point source pollution in the vadose zone. Geophysical Monogr 108: AGU, Washington, DC, USA, pp 1–20

Dev MS (2012) Small farmers in India: Challenges and opportunities. WP-2012-014. http://www.igidr.ac.in/pdf/publication/WP-2012-014.pdf. Accessed 4 Jan 2019

Dhillon BS, Kataria P, Dhillon PK (2010) National food security vis-a-vis sustainability of agriculture in high crop productivity regions. Curr Sci 98:33–36

Directorate of Economics & Statistics (2016) Agricultural statistics at a glance. http://eands.dacnet.nic.in/. Accessed 21 Aug 2017

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. Soil Science Society of America Inc, Madison, pp 3–21

Du T, Kang S, Zhang J, Davies WJ (2015) Deficit irrigation and sustainable water-resource strategies in agriculture for China's food security. J Exp Bot 66:2253–2269. https://doi.org/10.1093/jxb/erv034

Eagan S, Dhandayuthapani UN (2019) Organic agriculture: techniques to improve crop production. In eco-friendly agro-biological

techniques for enhancing crop productivity. Springer, Singapore, pp 1–24
Economic Intelligence Unit (EIU) (2017) Global Food security Index. http://foodsecurityindex.eiu.com/, Accessed 20 Oct 2017
Ehrlich PR, Harte J (2015) Food security requires a new revolution. Int J Environ Stud 72:908–920. https://doi.org/10.1080/00207233.2015.1067468
Eitzinger J, Singh S, Singh D (2009) Impacts of climate change and variability on agriculture–Experience from Europe and India. J Agromet 11:24–32
FAO (2011) Current world fertilizer trends and outlook to 2015. Food and Agricultural Organizations of United Nations, Rome, p 41
FAO (2015) The state of food insecurity in the world 2015. Food and Agricultural Organizations of United Nations, Rome
Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Zaks DPM et al (2011) Solutions for a cultivated planet. Nature 478:337–342. https://doi.org/10.1038/nature10452
Galloway J, Raghuram N, Abrol YP (2008) A perspective on reactive nitrogen in a global, Asian and Indian context. Curr Sci 94:1375–1381
Galvez L, Douds DD Jr, Drinkwater LE, Wagoner P (2001) Effect of tillage and farming system upon VAM fungus populations and mycorrhizas and nutrient uptake of maize. Plant Soil 228:299–308
Garcıa C, Hernandez T, Costa F (1994) Microbial activity in soils under Mediterranean environmental conditions. Soil Biol Biochem 26:1185–1191
Gattinger A, Muller A, Haeni M, Skinner C, Fliessbach A, Buchmann N, Mader P, Stolze M, Smith P, El-Hage Scialabba N, Niggli U (2012) Enhanced top soil carbon stocks under organic farming. Proc Natl A Sci USA 109:18226–18231
Ghosh PK, Das A, Saha R, Kharkrang E, Tripathy AK, Munda GC, Ngachan SV (2010) Conservation agriculture towards achieving food security in north East India. Curr Sci 99:915–921
Gill SS, Tuteja N (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol Biochem 48:909–930
Global Agricultural Productivity (GAP) report (2014) Global revolutions in agriculture: the challenge and promise of 2050. Global Harvest Initiative, Washington, D.C. 2006, USA
Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Toulmin C et al (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818. https://doi.org/10.1126/science.1185383
Gourley CJP, Allan DL, Russelle MP (1994) Plant nutrient efficiency: a comparison of definitions and suggested improvements. Plant Soil 158:29–37
Government of India (GOI) (2014) All India Reports on Number and Area of Agricultural Holdings from 1976–77, 1980–81, 1990–91, 2000–01, 2005–06 and 2010–11. Agricultural Census Division, Department of Agriculture and Co-operation, New Delhi
Government of India (GOI) (2016) Annual Report 2016–17. Department of Animal Husbandry, Dairying & Fisheries Ministry of Agriculture and Farmers Welfare, Government of India
Grinsven HJM, Erisman JW, Vries W, Westhoek H (2015) Potential of extensification of European agriculture for a more sustainable food system, focusing on nitrogen. Environ Res Letters 10:025002. https://doi.org/10.1088/1748-9326/10/2/025002
Gryndler M, Hrselová H, Sudová R, Gryndlerová H, Rezácová V, Merhautová V (2005) Hyphal growth and mycorrhiza formation by the arbuscular fungus *Glomus calaroideum* BEG23 is stimulated by humic substances. Mycorrhiza 15:483–488
Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc B Biol Sci 363:543–555
Huang S, Wang L, Liu L, Hou Y, Li L (2015) Nanotechnology in agriculture, livestock, and aquaculture in China. A review. Agron Sustain Dev 35:369–400
Indian Council for Agricultural Research (ICAR) (2010) Degraded and wastelands of India: status and spatial distribution. Indian Council for Agricultural Research, New Delhi
INECC (2010) The semi-arid region (2010). http://www.ced.org.in/docs/inecc/aridçbooklet/Arid-3-Arids.pdf. Accessed 20 Apr 2014
International Fund for Agricultural Development (IFAD) (2012) Sustainable smallholder agriculture: feeding the world, protecting the planet. International Fund for Agricultural Development, Rome, p 12
Jaiswal DK, Verma JP, Prakash S, Meena VS, Meena RS (2016) Potassium as an important plant nutrient in sustainable agriculture: a state of the art. Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi, pp 21–29
Jansson C, Wullschleger S, Kalluri U, Tuskan G (2010) Phytosequestration: carbon biosequestration by plants and the prospects of genetic engineering. Bioscience 60:685–696
Jat ML, Malik RK, Saharawat YS, Gupta R, Bhag M, Raj P (2012) Proceedings of regional dialogue on conservation agricultural in South Asia. New Delhi, India, APAARI, CIMMYT, ICAR, p. 32
Kaur S, Lubana PP, Aggarwal R (2013) Groundwater management for adaptation under changing climate conditions in Indian Punjab. J Water Clim Change 4:38–51
Kohli SS, Mitra BN (1987) Effects of azolla as an organic source of nitrogen in rice-wheat cropping systems. J Agron Crop Sci 159:212–215
Kolawole OD (2001) Local knowledge utilization and sustainable rural development in the 21st century. Indig Knowl Dev Monit 9:13–15
Kumar P, Mittal S (2006) Agricultural productivity trends in India: sustainability issues. Agric Econ Res Rev 19:71–88
Kumar R, Singh J (2003) Regional water management modeling for decision support in irrigated agriculture. J Irrig Drain Eng ASCE 129:432–439
Kumar M, Singh DP, Prabha R, Sharma AK (2015) Role of cyanobacteria in nutrient cycle and use efficiency in the soil. Nutrient use efficiency: from basics to advances. Springer, New Delhi, pp 163–171
Kumari T, Singh R, Verma P (2019) Agriculture, forests and environmental management trinity: towards environmental sustainability and climate change mitigation. Trop Ecol. https://doi.org/10.1007/s42965-019-00025-0
Kuppusamy S, Thavamani P, Megharaj M, Venkateswarlu K, Naidu R (2016) Agronomic and remedial benefits and risks of applying biochar to soil: current knowledge and future research directions. Environ Int 87:1–12. https://doi.org/10.1016/j.envint.2015.10.018
Lal R (2005) World crop residue production and implications of its use as biofuel. Environ Int 31:575–584
Lal R (2007) Managing soils for food security and climate change. J Crop Impr 19:49–71
Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustainability 7:5875–5895. https://doi.org/10.3390/su7055875
Lal R (2016) Potential and challenges of conservation agriculture in sequestration of atmospheric CO2 for enhancing climate-resilience and improving productivity of soil of small landholder farms. CAB Rev 11:1–16
Lichtfouse E, Navarrete M, Debaeke P, Souchère V, Alberola C, Ménassieu J (2009) Agronomy for sustainable agriculture: a review. Agron Sustain Dev 29:1–6
Lobell DB, Baldos ULC, Hertel TW (2014) Climate adaptation as mitigation: the case of agricultural investments. Environ Res Lett 8:1–12. http://iopscience.iop.org/1748-9326/8/1/015012

Luo Z, Wang E, Sun OJ (2010) Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: a review and synthesis. Geoderma 155:211–223

Mahajan A, Gupta RD (2009) Integrated Nutrient Management (INM) in a sustainable rice-wheat cropping system. Springer, New York. https://doi.org/10.1007/978-1-4020-9875-8

Mahapatra BS, Ramasubramanian T, Chowdhury H (2009) Organic farming for sustainable agriculture: global and Indian perspective. Indian J Agron 54:178–185

Majumdar K, Dey P, Tewatia RK (2014) Current nutrient management approaches. Indian J Fertil 10:14–27

Mall RK, Singh R, Gupta A, Srinivasan G, Rathore LS (2006) Impact of climate change on Indian agriculture: a review. Clim Change 78:445–478

Mander U, Mikk M, Kulvik M (1999) Ecological and low intensity agricultureas contributors to landscape and biological diversity. Landsc Urban Plann 46:169–177

Meena VS, Sharma S (2015) Organic farming: a case study of Uttarakhand organic commodity board. J Indian Poll Con. http://www.icontrolpollution.com/articles/organic-farming-a-case-study-of-uttarakhand-organic-commodity-board-.php?aid=65718. Accessed 4 Jan 2019

Meena VS, Maurya BR, Bahadur I (2014) Potassium solubilization by bacterial strain in waste mica. Bang J Bot 43:235–237

Millennium Ecosystem Assessment (MEA) (2005) Ecosystems and human well-being. Scenarios: findings of the scenarios working group, vol 2. Island, Washington, DC

Ministry of Agriculture (2015) State of Indian agriculture. http://agricoop.nic.in/Annual%20report2012-13/ARE2012-13.pdf. Accessed 4 Jan 2019

Ministry of Home Affairs (2011) Government of India. http://censusindia.gov.in/2011-provresults/indiaatglance.html. Accessed 4 Jan 2019

Mishra A, Whitten M, Ketelaar JW, Salokhe V (2007) The system of rice intensification (SRI): a challenge for science, and an opportunity for farmer empowerment towards sustainable agriculture. Int J Agric Sustain 4:193–212

Mishra A, Kumar P, Noble A (2013) Assessing the potential of SRI management principles and the FFS approach in Northeast Thailand for sustainable rice intensification in the context of climate change. Intl J Agric Sustain 11:4–22. https://doi.org/10.1080/14735903.2012.658648

Mitra AP (1992) Greenhouse gas emission in India: 1991, Methane Campaign. Science Report No. 2, Council of Scientific and Industrial Research and Ministry of Environment & Forests, New Delhi, India

Mittal V, Singh O, Nayyar H, Kaur J, Tewari R (2008) Stimulatory effect of phosphate-solubilizing fungal strains (*Aspergillus awamori* and *Penicillium citrinum)* on the yield of chickpea (*Cicer arietinum* L. cv. GPF2). Soil Biol Biochem 40:718–727

Mohanty A, Wu Y, Cao B (2014) Impacts of engineered nanomaterials on microbial community structure and function in natural and engineered ecosystems. Appl Microbiol Biotechnol 98:8457–8468

Mtengeti EJ, Brentrup F, Mtengeti E, Eik LO, Chambuya R (2015) Sustainable intensification of Maize and Rice in smallholder farming systems under climate change in Tanzania. In: Lal R et al (eds) Sustainable intensification to advance food security and enhance climate resilience in Africa. Springer, Switzerland, pp 441–465. https://doi.org/10.1007/978-3-319-09360-4_24

Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS (2010) Nanoparticulate material delivery to plants. Plant Sci 179:154–163. https://doi.org/10.1016/j.plantsci.2010.04.012

Narwal SS (2010) Allelopathy in ecological sustainable organic agriculture. Allelopathy J 25:51–72

Nath AJ, Lal R, Sileshi GW, Das AK (2018) Managing India's small landholder farms for food security and achieving the "4 per Thousand" target. Sci Total Environ 634:1024–1033

Neelam AA, Gaur A, Bhalla E, Gupta SR (2010) Soil aggregate carbon and diversity of mycorrhiza as affected by tillage practices in a rice-wheat cropping system in northern India. Int J Ecol Environ Sci 36:233–243

Nelson GC et al (2010) Food security, farming, and climate change to 2050: scenarios, results, policy options. International Food Policy Research Institute, Washington, DC

Olsson PA, Thinstrup I, Jakobsen I, Bååth E (1999) Estimation of the biomass of arbuscular mycorrhizal fungi in a linseed field. Soil Biol Biochem 31:1879–1887

Pal DK, Wani SP, Sahrawat KL (2015) Carbon sequestration in Indian soils: present status and the potential. Proc Natl Acad Sci India Sect B Biol Sci 85:337–358. https://doi.org/10.1007/s40011-014-0351-6

Pandey C, Diwan H (2018) Integrated approach for managing fertilizer intensification linked environmental issues. Manag Environ Qual Int J 29:324–347

Paul B, Vanlauwe B, Ayuke F, Gassner A, Hoogmoed M, Hurisso T, Koala S, Lelei D, Ndabamenye T, Six J (2013) Medium-term impact of tillage and residuemanagement on soil aggregate stability, soil carbon and crop productivity. Agric Ecosyst Environ 164:14–22

Ponisio LC, M'Gonigle LK, Mace KC, Palomino J, de Valpine P, Kremen C (2015) Diversification practices reduce organic to conventional yield gap. Proc R Soc B Biol Sci. https://doi.org/10.1098/rspb.2014.1396

Prakash O, Sharma R, Rahi P, Karthikeyan N (2015) Role of microorganisms in plant nutrition and health. Nutrient use efficiency: from basics to advances 2015. Springer, New Delhi, pp 125–161

Pretty NJ (1995) Regenerating agriculture, policies and practices for sustainability and self-reliance. Earthscan Publication Limited, London, p 320

Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc Lond Ser B Biol Sci 363:447–466. https://doi.org/10.1098/rstb.2007.2163

Pretty JN, Noble AD, Bossi D, Dixon J, Hine RE, Penning De Vries FW (2006) Resource conserving agriculture increases yields in developing countries. Environ Sci Technol 40:1114–1119. https://doi.org/10.1021/es051670d

Pretty J, Sutherland WJ, Ashby J, Auburn J, Baulcombe D, Bell M, Pilgrim S et al (2010) The top 100 questions of importance to the future of global agriculture. Intl J Agric Sustain 8:219–236. https://doi.org/10.3763/ijas.2010.0534

Priyadharsini P, Muthukumar T (2015) Insight into the role of arbuscular mycorrhizal fungi in sustainable agriculture. Environmental sustainability. Springer, New Delhi, pp 3–37

Ramakrishna R, Rao DT (2008) Strengthening Indian Agriculture through Dryland Farming: need for reforms'. Indian J Agric Econ 63:460–476

Ramakrishnan PS (2007) Sustainable agriculture and food security: India–China context. China Rep 43:219

Ramankutty N, Evan AT, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob Biogeol Cyc 22:GB1003. https://doi.org/10.1029/2007gb002952

Rao DL, Balachandar D (2017) Nitrogen inputs from biological nitrogen fixation in Indian agriculture. In: The Indian nitrogen assessment: sources of reactive nitrogen, environmental and climate effects, management options, and policies, vol 14, p 117

Ritzema HP, Satyanarayana TV, Raman S, Boonstra J (2008) Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: lessons learned in farmers' fields. Agric Water Manage 95:179–189

RWC (Rice-Wheat Consortium) (2005) Rice-wheat cropping systems of indo-gangetic plains, New Delhi, India. Research highlights 2004
Saadatnia H, Riahi H (2009) Cyanobacteria from paddy fields in Iran as a biofertilizer in rice plants. Plant Soil Environ 55:207–212
Sah D, Devakumar AS (2018) The carbon footprint of agricultural crop cultivation in India. Carbon Manag 9:213–225
Saikia SP, Bora D, Goswami A, Mudoi KD, Gogoi A (2013) A review on the role of Azospirillumin on the yield improvement of non leguminous crops. Afr J Microb Res 6:1085–1102
Sanchez PA (2002) Soil fertility and hunger in Africa. Science 295:2019–2020
Sankar Ganesh KS, Sundaramoorthy P, Nagarajan M, Xavier RL (2017) Role of organic amendments in sustainable agriculture. Sustainable agriculture towards food security. Springer, Singapore, pp 111–124
Sarkar M, Datta S, Kundagrami S (2017) Global climate change and mung bean production: aroadmap towards future sustainable agriculture. In: Sustaining future food security in changing environment, p 99
Sathya A, Vijayabharathi R, Gopalakrishnan S (2016) Soil microbes: the invisible managers of soil fertility. Microbial inoculants in sustainable agricultural productivity. Springer, New Delhi, pp 1–16
Schmidhuber J, Tubiello FN (2007) Global food security under climate change. Proc Nat Acad Sci USA 104:19703–19708. https://doi.org/10.1073/pnas.0701976104
Searchinger TD, Wirsenius S, Beringer T, Dumas P (2018) Assessing the efficiency of changes in land use for mitigating climate change. Nature 564:249
Senthilkumar K, Bindraban P, Thiyagarajan T, De Ridder N, Giller K (2008) Modified rice cultivation in Tamil Nadu, India: yield gains and farmers' (lack of) acceptance. Agric Syst 98:82–94
Sharma SK (2002) A synoptic view of linkages of organic farming with productivity and sustainability of India. In: CAS training on organic agriculture—a paragon for sustainability held at JNKVV, Jabalpur, March 26th—April 15th, 2002, p 29
Sharma LC, Arora U (2006) Combating India's food problem by 2020. Ann Agric Bio Res 11:113–116
Sharma SK, Choudhury A, Sarkar P et al (2011) Greenhouse gas inventory estimates for India. Curr Sci 101:405–415
Sharma P, Kumawat KC, Kaur S (2016) Plant growth promoting rhizobacteria in nutrient enrichment: current perspectives. Biofortification of food crops. Springer, New Delhi, pp 263–289
Sheng M, Tang M, Chan H, Yang B, Zhang F, Huang Y (2008) Influence of arbuscular mycorrhizae on photosynthesis and water status of maize plants under salt stress. Mycorrhiza 18:287–296
Shiva V (1991) The green revolution in the Punjab. Ecologist 21:57–60
Shukla AK, Malik RS, Tiwari PK, Prakash C, Behera SK, Yadav H, Narwal RP (2015) Status of micronutrient deficiencies in soils of Haryana. Indian J Fert 11:16–27
Sihi D, Dari B, Sharma DK, Pathak H, Nain L, Sharma OP (2017) Evaluation of soil health in organic vs. conventional farming of basmati rice in North India. J Plant Nutr Soil Sci 180:389–406
Singh R (2000) Environmental consequences of agricultural development: a case study from the Green Revolution state of Haryana, India. Agric Ecosyst Environ 82:97–103
Singh RB (2001) Impact of land-use change on groundwater in the Punjab-Haryana plains, India. In: Impact of human activity on groundwater dynamics (Proceedings of a symposium held during the 6th IAHS Scientific Assembly at Maastricht, The Netherlands, July 2001). IAHS Publ. no. 269
Singh YV (2013) Crop and water productivity as influenced by rice cultivation methods under organic and inorganic sources of nutrient supply. Paddy Water Environ 11:531–542. https://doi.org/10.1007/s10333-012-0346-y
Singh J, Sidhu RS (2006) Accounting for impact of environmental degradation in agriculture of Indian Punjab. Agric Econ Res Rev 19:37–48
Singh R, Babu JN, Kumar R, Srivastava P, Singh P, Raghubanshi AS (2015a) Multifaceted application of crop residue biochar as a tool for sustainable agriculture: an ecological perspective. Ecol Eng 77:324–347. https://doi.org/10.1016/j.ecoleng.2015.01.011
Singh R, Srivastava P, Upadhyay S, Singh P, Raghubanshi AS, Babu JN (2015b) Integrating biochar as conservation agriculture tool under climate change mitigation scenario. In: Proceedings of national conference on climate change: impacts, adaptation, mitigation scenario and future challenges in Indian perspective
Singh R, Srivastava P, Singh P, Raghubanshi AS (2016a) Sustainability indicators of the emergent agronomic practices: An Indian perspective. In: Gurjar BR, Molina LT (eds) Environmental science & engineering: climate change and sustainable technology, vol 12. Studium, New York, pp 142–166
Singh OP, Singh R, Lakra K, Singh PK (2016b) Impact of zero tillage on environment and wheat productivity: evidences from gorakhpur district of eastern Uttar Pradesh, india. Int J Agric Stat Sci 12:21–28
Singh P, Singh R, Borthakur A, Srivastava P, Srivastava N, Tiwary D, Mishra PK (2016c) Effect of nanoscale TiO_2-activated carbon composite on *Solanum lycopersicum* (L.) and *Vigna radiata* (L.) seeds germination. Energy Ecol Environ 1:131–140
Singh R, Srivastava P, Singh P, Upadhyay S, Raghubanshi AS (2017) Human overpopulation and food security: challenges for the agriculture sustainability. In: Environmental issues surrounding human overpopulation. IGI Global, pp 12–39
Singh R, Srivastava P, Singh P, Sharma AK, Singh H, Raghubanshi AS (2019a) Impact of rice-husk ash on the soil biophysical and agronomic parameters of wheat crop under a dry tropical ecosystem. Ecol Indian 105:505–515
Singh R, Singh P, Singh H, Raghubanshi AS (2019b) Impact of sole and combined application of biochar, organic and chemical fertilizers on wheat crop yield and water productivity in a dry tropical agro-ecosystem. Biochar 1:229–235. https://doi.org/10.1007/s42773-019-00013-6
Smil V (2002) Nitrogen and food production: proteins for human diets. Ambio 31:126–131. https://doi.org/10.1579/0044-7447-31.2.126
Solanki P, Bhargava A, Chhipa J, Jain N, Panwar J (2015) Nano-fertilizers and their smart delivery system. In: Rai M, Ribeiro C, Mattoso L, Duran N (eds) Nanotechnologies in food and agriculture. Springer, Cham, pp 81–101
Somasundaram E, Asoka Raja N, Mohamed Amanullah M, Nandhini DU (2015) A guide to organic farming. University Press, Tamil Nadu Agricultural University, Coimbatore, 641003, India
Somers E, Vanderleyden J, Srinivasan M (2004) Rhizospherebacterial signalling: a love parade beneath our feet. Crit Rev Microbiol 30:205–240
Song T, Martensson L, Eriksson T, Zheng W, Rasmussen U (2005) Biodiversity and seasonal variation of the cyanobacterial assemblage in a rice paddy field in Fujian, China. Fed Eur Mat Soc Microbiol Ecol 54:131–140
Souza BD, Rao KRM (2016) Challenges in achieving food security in India. Asian J Microb Biotech Environ Sci 18:957–961
Sreenivas K, Dadhwal VK, Kumar S, Harsha GS, Mitran T, Sujatha G, Suresh GJR, Fyzee MA, Ravisankar T (2016) Digital mapping of soil organic and inorganic carbon status in India. Geoderma 269:160–173
Srivastava P, Raghubanshi AS, Singh R, Tripathi SN (2015) Soil carbon efflux and sequestration as a function of relative availability of inorganic N pools in drytropical agroecosystem. Appl Soil Ecol 96:1–6
Srivastava P, Singh R, Tripathi S, Raghubanshi AS (2016) An urgent need of sustainable thinking in agriculture—an Indian

scenario. Ecol Indian 67:611–622. https://doi.org/10.1016/j.ecolind.2016.03.015
Srivastava P, Singh R, Tripathi S, Singh H, Raghubanshi AS, Mishra PK (2018) A new insight into the warming potential of organically amended agro-ecosystems. Organ Agric 8:275–284
Stoop WA, Uphoff N, Kassam A (2002) A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. Agric Syst 71:249–274
Suman A, Yadav AN, Verma P (2016) Endophytic microbes in crops: diversity and beneficial impact for sustainable agriculture. Microbial inoculants in sustainable agricultural productivity. Springer, New Delhi, pp 117–143
Tallapragada P, Seshachala U (2012) Phosphatesolubilizing microbes and their occurrence in the rhizospheres of Piper betel in Karnataka, India. Turk J Biol 36:25–35
Thamdrup B (2012) New pathways and processes in the global nitrogen cycle. Annu Rev Ecol Evol Syst 43:407–428
Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature 418:671–677. https://doi.org/10.1038/nature01014
Torney F, Trewyn BG, Lin VSY, Wang K (2007) Mesoporous silica nanoparticles deliver DNA and chemicals into plants. Nat Nanotechnol 2:295–300
Umarani R, Subramaniyan K (2000) Modernization of agriculture—a boon or bane? Curr Sci 79:1515
UNPD (2007) http://www.un.org/en/development/desa/population/. Accessed 4 Jan 2019
Uphoff N, Kassam A, Harwood R (2011) SRI as a methodology for raising crop and water productivity: productive adaptations in rice agronomy and irrigation water management. Paddy Water Environ 9:3–11. https://doi.org/10.1007/s10333-010-0224-4
Vermeulen SJ, Aggarwal PK, Ainslie A, Angelone C, Campbell BM, Challinor AJ, Wollenberg E et al (2012) Options for support to agriculture and food security under climate change. Environ Sci Policy 15:136–144. https://doi.org/10.1016/j.envsci.2011.09.003
Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737–750
Wakeyo MB, Gardebroek C (2017) Share of irrigated land and farm size in rainwater harvesting irrigation in Ethiopia. J Arid Environ 139:85–94
Warren MD (1993) Using indigenous knowledge in agricultural development. The World Bank, Washington, DC
Wichelns D, Oster JD (2006) Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. Agric Water Manage 86:114–127
Wolf J, Bindraban PS, Luijten JC, Vleeshouwers LM (2003) Exploratory study on the land area required for global food supply and the potential global production of bioenergy. Agric Syst 76:841–861
World Bank (2008) World Development Report 2008: agriculture for development. World Bank, Washington, DC
Yan M, Cheng K, Luo T, Yan Y, Pan G, Rees RM (2015) Carbon footprint of grain crop production in china- based on farm survey data. J Clean Prod 104:130–138. https://doi.org/10.1016/j.jclepro.2015.05.058
Zeng F, Ali S, Zhang H, Ouyang Y, Qiu B, Wu F, Zhang G (2011) The influence of pH and organic matter content in paddy-soil on heavy metal availability and their uptake by rice plants. Environ Poll 159:84–91
Zhang C, Kong F (2014) Isolation and identification of potassium-solubilizing bacteria from tobacco rhizospheric soil and their effect on tobacco plants. Appl Soil Ecol 82:18–25