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# Organic rice: potential production strategies, challenges and prospects

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**Abstract** Organic farming is rapidly gaining recognition worldwide as a promising means to offer healthier food and to ensure environmental sustainability. Currently, organic produce including organic rice is in huge demand owing to its potential to fetch premium price in the global market. Despite the fact that rice performs well under organic production system, a set of constraints including nitrogen stress at critical growth stages, unavailability of rapidly mineralizable organic amendments, lack of appropriate varieties and intense crop–weed competition pose major challenges to realize the potential yield. Use of diverse organic nutrient sources including the split application of fast mineralizable nutrient-rich manures (vermicompost, poultry manure), green manures and bio-fertilizers can supply optimum nutrients in organic rice system. In parallel, development and deployment of rice varieties having response to organic nutrient inputs, resistance to diseases/insects and ability to compete with weeds can help minimize the risk of crop failure. Further, higher emission of greenhouse gases (GHGs) in organic rice field deserves greater attention in view of environmental sustainability. Strategic water management and selection of appropriate organic amendments could help address this issue. However, a substantial research gap still exists demanding a deeper understanding of the organic rice system in order to register higher yield gains. This review article outlines the latest advances in organic rice production system with an emphasis on nutrient supply and ensuing dynamics, the outflow of GHGs, pest dynamics, produce quality and key attributes of rice cultivars for organic cultivation. We underscore the urgency for alignment of modern agricultural techniques with organic rice production to improve both the system productivity and the produce quality along with effectively avoiding the risks associated with in discriminate use of chemicals in agriculture.

**Keywords** Grain quality · Methane emission · Nutrient stress · Organic rice · Pest dynamics · Yield

## Introduction

The demand of organic food products is rising rapidly across the world. Recent trend illustrates remarkable expansion in market size of organic produce from US$ 15.2 billion in 1999 to 63.9 billion in 2012 and is anticipated to grow at higher growth rate in the coming years (IFOAM 2013) (Fig. 1). In general, countries with higher income have greater demands for organic foods. For instance, the USA has the largest market size (US$ 29 billion) followed by Germany (US$ 9.2 billion) and France (US$ 5.2 billion).

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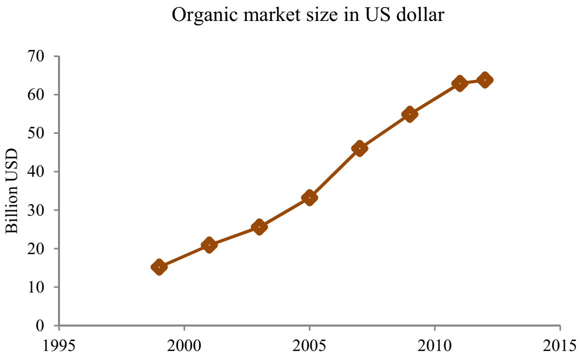

**Fig. 1.** Trend of global organic market in US dollar (USD) (IFOAM 2013)

Meanwhile, the developing countries particularly South Asian countries have also witnessed significant growth in organic food market in recent years. The growing concern about the ill effects of intensive use of chemicals in agriculture has paved the way to embrace organic farming worldwide (Prasad 2005). Also, the demand for organic rice has also increased in recent years that have eventually created a considerable gap between demand and supply. Therefore, to harness the global organic rice market, the area coverage and productivity of organic rice urgently need a dramatic increase.

Organic agriculture is generally considered as sustainable production system due to less use of off–farm inputs, higher input–output efficiency and environmental benefits (Singh et al. 2005; Badgley et al. 2006; Chouichom and Yamao 2010). Adoption of organic agriculture would help to mitigate the problems associated with input intensive conventional agriculture (Lynggaard 2006; Wheeler 2008).

The concept of organic rice farming is not very new. It was practiced traditionally by the farming communities, particularly in some states of India such as Sikkim, Arunachal Pradesh, Manipur and Uttarakhand where resource-poor farmers could not afford chemical fertilizers (Pandi et al. 2013). However, the productivity of these organic rice systems is quite low as compared to the input-intensive conventional agriculture (Andersen et al. 2015).

As reported in several studies, the average yield of cereal crops in organic farming is less than obtained from conventional production practices (Bhattacharyya et al. 2003; Sarkar et al. 2003; Rautaray et al. 2003). This is primarily due to difficulties in plant nutrient management and lack of effective pest management options. Among the cereals, performance of rice under organic farming has been found fairly impressive (Zhang et al. 2005; Delmotte et al. 2011). The comparatively higher yield of rice in organic farming than other cereal crops was evident in a recent multi-location study, where organic to conventional relative yield (per cent) manifested the following order: rice (94) > corn (89) > oats (85) > rye (76) > wheat (73) > barley (69) (de Ponti et al. 2012). To this end, the flooded anaerobic rice cultivation could offer additional advantage in organic farming when compared with other field crops (Hazra et al. 2014). This in turn indicates that the rice crop responds favourably to organic management and can be popularized under organic farming in rice-growing areas.

Despite witnessing a rapid expansion in some countries over the last two decades (Zikeli et al. 2014; van Bruggen et al. 2016), organic agriculture is still in its infancy in most of the developing countries. The considerable yield gap in rice yield between conventional and organic production systems is one of the key factors that impede its large-scale adoption among farmers. Of the various yield-limiting factors, suboptimal nutrient input (nitrogen in particular) (Stockdale et al. 2002; Wild et al. 2011; Hazra et al. 2014), non-availability of organic resources, lack of low-input responsive varieties (Lammerts van Bueren et al. 2011), severe crop–weed competition (Hokazono and Hayashi 2012) and insect and disease damage (Kiritani 2007) exert major impact on most of the organic rice-growing areas. An improved understanding about organic rice production involving plant nutrient stress, soil nutrient dynamics, soil–plant–microbes interaction and pest dynamics is essential to adequately address the above-stated issues. Moreover, production techniques require optimization in order to deliver maximum harvest while retaining the quality standards of organic rice. In recent years, many Asian countries could emerge as potential exporters of organic rice, especially for basmati and aromatic rice. For example, India exported 5630 million tonnes of organic basmati rice through agricultural and processed food products export development authority (APEDA) during 2008–2009 (Pandi et al. 2013). In this article, we review the current knowledge on organic rice farming with an attempt to identify the critical constraints. We suggest potential production strategies for improving the existing system and highlight future researchable areas.

## Understanding organic rice ecology and production system

Identification of crucial yield-limiting factors and understanding the system ecology and production system enable us to devise attractive strategies for efficient organic rice production.

### Nutrient availability in organic rice soil

Nutrient management has remained a key challenge in organic farming. Rice being a fast growing crop requires plenty of plant nutrients; and this demand swells considerably in case of modern high-yielding varieties (HYVs). Since organic farming is normally operated in closed system of organic input and nutrients (Stockdale et al. 2001), ensuring optimum nutrient availability throughout the crop growing period becomes practically difficult. Under organic rice production system, the non-synchrony between the stage wise demand and the mineralization rate of added organic matter often causes nutrient stress at critical growth stages. Since nutrient release from organic manure sources is slower than that of the inorganic fertilizers, the capacity of organic system to supply nutrients (nitrogen in particular) largely depends on the timing and pattern of mineralization and its synchrony with the crop's demand (Berry et al. 2002; Sacco et al. 2015).

Nitrogen (N) is considered as the critical limiting nutrient in irrigated rice, particularly in organic production systems (Eltun 1996; Berry et al. 2002; Wild et al. 2011; Huang et al. 2016). Precisely putting the N supply in sync with its demand is extremely difficult in organic rice production (Jarvis et al. 1996). In principal, all nitrifiers are obligate aerobes; hence, the reduced oxidation level in flooded rice condition further restricts the soil N mineralization of organic matter (Robertson and Groffman 2015). By contrast, system of rice intensification (SRI), where non-flooded aerobic condition is maintained, substantially improves the rate of N mineralization and also enhances secretion of some enzymes (e.g., protease) that promote the activity of microorganisms (Ceesay et al. 2006). The release of N during the growing period is usually less in organic rice soils, and the rate of release mainly depends on the mineralization rate, which in turn is influenced by a variety of factors such as frequency of drying cycles, N density in added organic amendments, soil temperature and moisture (Prasad 2005; Lammerts van Bueren et al. 2011; Robertson and Groffman 2015).

The availability of N in organic rice soil differs markedly between rice production systems with contrasting water regimes, i.e., flooded anaerobic and non-flooded aerobic. Mineralization rate of added organic N in flooded rice soils (anaerobic) is very slow in contrast to the non-flooded rice (aerobic) soils albeit the later renders N prone to potential losses. Oxygen supply via converting $NH_4^+$ to $NO_3^-$ (nitrification) accelerates breakdown of organic matter. Re-flooding imposes an anaerobic condition where the newly formed $NO_3^-$ is lost through denitrification and leaching. For that reason, optimization of water regime is very crucial in maintaining the availability of N in organic rice soils (Neeson 2005). Moreover, submerged conditions also facilitate higher N fixation in organic rice soils. Under triple-cropped submerged rice soil condition, relatively higher proportion of amide N bonded to aromatic ring in a humic acid reduces the availability of soil available N (Schmidt-Rohr et al. 2004). The long-run organic system capable of retaining higher soil organic carbon (SOC) permits partial compensation for the negative impact (caused by reduced N availability) through improving physical and biological properties as well as nutrient retention capacity of the soil (Lammerts van Bueren et al. 2002). Therefore, the crop yield under organic rice system might be low due to a gamut of factors including reduced N availability, suboptimal application rate and uncontrollable release of N.

Unlike N, the information on deficiency of phosphorus (P) and potassium (K) in organic rice production is scanty, and not much effort has been dedicated towards assessing the P and K accessibility to rice in organic system. Enhanced levels of soil organic C, soluble P and $NH_4OAC$ extractable K can be maintained in organic soil by applying greater quantities of inputs carrying these nutrients (Clark et al. 1998). Higher P and K inputs are reported in organic farming than the conventional system due to the abundance of animal manure with lower N:P and N:K ratios (Gosling and Shepherd 2005; Borda et al. 2011). Likewise, crop balance surplus in organic farming is generally positive for P (Bassanino et al. 2011; Sacco et al. 2015) and K (Berry et al. 2002; Gopinath et al. 2008).

Response to P under flooded rice is usually poor because flooding decreases soil P sorption and increases P diffusion which eventually leads to a higher P supply to rice (Singh et al. 2000). In fact, the availability of P increases in the flooded rice soils because of the reduction of ferric phosphate to the more soluble ferrous form. Likewise, in flooded alkaline soils, release of P from Ca and $CaCO_3$ due to flood-induced decrease in pH improves the availability and uptake of P from rice soil (Fageria et al. 2011). Taken together, the possibility of flood-induced changes in P availability may be discarded in case of non-flooded aerobic rice cultivation. Concomitantly, an increased oxidation level might improve the mineralization of organic P and compensate for the impact of flooding on P availability. However, the P availability and accessibility in aerobic vs. anaerobic rice cultivation scenarios remain to be investigated thoroughly.

During the decomposition process of added organic amendments, $H^+$ ions are released and this induced acidification in turn helps solubilize the fixed or native soil P. Research on this aspect has revealed that citrate released from the rice roots improves P absorption even in P-deficient soils (Liu et al. 1990; Kirk et al. 1999). Along this line, Nakajima et al. (1993) compared 13 pairs of paddy soils managed organically and conventionally, and they found lower Truog–P in organic managements. By contrast, Hasegawa et al. (2005) observed no significant differences in Truog–P under organic and conventional rice soils. In this way, the P-related stress is not much apparent in organic rice production system. However, the restricted uptake of P under N-limiting condition in organic rice system could be adequately explained on the basis of "Liebig's law of minimum". This creates enormous scope for applying efficient bio-fertilizers to improve the P availability in organic farming. In this regard, mycorrhiza is especially important as intermediaries that enable plants for P uptake (Lammerts van Bueren et al. 2011).

Under organic management, K dynamics is also different from that recorded in conventional systems. A comparative study of conventional and organic paddy soils with different length after conversion from conventional management revealed that longer is the duration after the conversion lowers the $NH_4OAC$ extractable K (Tamaki and Nakagawa 1997). As rice extracts large amount of K from soil, higher K input is needed for long-term sustainability of organic rice system. Adequate quantity of organic amendments allows meeting required micronutrients as well as their availability in organic rice crop. Hence, the deficiency of micronutrient is rarely encountered under organic rice system.

## Plant nutrient supply in organic rice

Organic materials significantly differ with respect to C:N ratio, nutrient content and nutrient release rate, which renders monitoring of the transformation of supplied organic inputs essential in rice ecosystem (Venkateswarlu et al. 2008; Monaco et al. 2008). Significant attention has been given to measure the impact of supplemental or integrated application of organic matter in combination with inorganic fertilizers for rice crop. However, the response of rice crop to only organic amendment/s without any chemical nutrient supplementation in rice production system is not examined adequately.

A range of organic amendments including fly ash (Rautaray et al. 2003; Mittra et al. 2005), farm yard manure (FYM) (Nguyen Van et al. 2002; Sarkar et al. 2003; Usman et al. 2003; Rasool et al. 2007), poultry manure (Usman et al. 2003), oil cake pallets (Bhadoria et al. 2003), cattle manure (Saha et al. 2010), cow dung manure (Bhattacharyya et al. 2003), winter weeds (Saha et al. 2007), vermicompost (Bhadoria et al. 2003), compost and straw incorporation (Rasool et al. 2007) and pig manure (Xu et al. 2008) were evaluated under flooded rice system. The relative efficacy of these amendments as compared to the recommended inorganic fertilization is shown in Table 1. Lager variation in the relative effectiveness of these organic nutrient inputs was apparent with changes in input quantity, soil type, rice variety and time of application.

As illustrated in Table 2, researchers have also analyzed combinations of various sources of organic inputs in organic rice production system (Jeyabal and Kuppuswamy 2001; Nguyen et al. 2002; Van Quyen and Sharma 2003; Deshpande and Devasenapathy 2010). In general, the relative effectiveness of combined/integrated application was superior in all the experiments over application of only one organic source. Based on the results arising from several studies, it could be inferred that the average reduction in rice grain yield was ~8% when plant nutrient supplied through only one organic sources (e.g., only FYM, only green manuring) compared with the recommended fertilizer rate. In the same line, we quantified that integrated application of different sources of organic inputs can increase rice yield by ~10% over inorganic fertilizer rate in different locations (Fig. 2). For strategic nutrient management under organic rice, it is always better to have diverse sources rather than relying on sole component and importantly, meeting the total nutrient demand from one source remains difficult. This calls for an integrative

**Table 1** Relative effectiveness of different organic amendments for organic rice production

| Organic source/s | Quantity (ha) | Inorganic fertilizer rate | Soil type | Rice variety | Grain yield (kg ha$^{-1}$) | | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | Organic | Inorganic | |
| Cattle manure (CM) | Equivalent NPK supplied by CM @ 20 t ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam | SRSN-18 | 5180 | 5060 | Saha et al. (2010) |
| Cattle manure (CM) | Containing 16.1, 5.47, 6.22 g N, P, K per kg CM;<br>completely substituted the full dose of recommended NPK | Jinxian (160: 16.4: 100) Nanchang (150: 26.2: 125)<br>Qiyang (72.5: 24.6: 28) | Long-term multi-location study | Jinxian<br>Nanchang<br>Qiyang | 5310 | 5290 | Bi et al. (2009) |
| Cow dung manure (CDM) | CDM @ 5.08–5.26 t ha$^{-1}$ applied alone to supply 60 kg N ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 60:30:30 kg ha$^{-1}$ | Gangetic alluvial soil | IET-1444 | 3260 | 3910 | Bhattacharyya et al. (2003) |
| Farmyard manure (FYM) | FYM @ 3 t ha$^{-1}$ to meet 100% N of recommended fertilizer dose | N:$P_2O_5$:$K_2O$ 80:40:30 kg ha$^{-1}$ | Fine loamy soil | Akashi | 1576 | 2157 | Sarkar et al. (2003) |
| Farmyard manure (FYM) | FYM alone @ 20 t ha$^{-1}$, applied at the time of pre-puddling tillage | N:$P_2O_5$:$K_2O$ 120:30:30 kg ha$^{-1}$ | Sandy loam | PR114 | 7920 | 777 0 | Rasool et al. (2007) |
| Farmyard manure (FYM) | FYM was applied at 10 t ha$^{-1}$ at the time of final puddling | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam, | Pusa Basmati 1 | 4200 | 4470 | Nguyen Van et al. (2002) |
| Fly ash | Fly ash @10 t ha$^{-1}$ | N:P:K 90:26: 68 kg ha$^{-1}$ | Lateritic sandy loam | IR36 | 3073 | 3781 | Rautaray et al. (2003) |
| Fly ash | Fly ash @10 t ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 90: 60: 40 kg ha$^{-1}$ | Lateritic sandy loam | IR36 | 2208 | 3745 | Mittra et al. (2005) |
| *Sesbania* green manure (SGM) | SGM was grown for 60 days and was incorporated 5 days before transplanted. | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 4720 | 4470 | Nguyen Van et al. (2002) |
| Green manure (Astragalus L) | Green manure @ 45 t ha$^{-1}$ | N:P:K 160: 16.4: 100 kg ha$^{-1}$ | Silty loam | – | ~8050 | ~8050 | Liu et al. (2009) |
| Municipal solid waste compost (MSWC) | MSWC @ 5.9–6 t ha$^{-1}$ applied alone to supply 60 kg N ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 60:30:30 kg ha$^{-1}$ | Gangetic alluvial soil | IET-1444 | 2820 | 3910 | Bhattacharyya et al. (2003) |
| Oil cake pellets | Applied N equivalent basis (100% N). Additionally Supplied 57 kg $P_2O_5$ and 24 kg $K_2O$ ha$^{-1}$ | N:P:K 80: 26:42 kg ha$^{-1}$ | Lateritic soils | Pusa Basmati | 3100 | 3200 | Bhadoria et al. (2003) |
| Pig manure | Applied @ 25 t ha$^{-1}$ pig manure-dry matter weight | N:P:K 150: 43.7:90.9 kg ha$^{-1}$ | Heavy clay | Xiangliangyou-68 | 11,612 | 11,702 | Xu et al. (2008) |
| Poultry manure | Poultry manure @ 20 t ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 100:75:60 kg ha$^{-1}$ | - | Basmati–2000 | 2410 | 3160 | Usman et al. (2003) |
| Processed city wasted | Applied N equivalent basis (100% N). Additionally supplied 48 kg $P_2O_5$ and 59 kg $K_2O$. | N:P:K 80: 26:42 kg ha$^{-1}$ | Lateritic soils | Pusa Basmati | 3500 | 3200 | Bhadoria et al. (2003) |

**Table 1** (continued)

| Organic source/s | Quantity (ha) | Inorganic fertilizer rate | Soil type | Rice variety | Grain yield (kg $ha^{-1}$) | | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | Organic | Inorganic | |
| *Sesbani*a green manure (SGM) | *Sesbania* was grown for 60 days and was incorporated | N:P:K 180:39:51 kg $ha^{-1}$ | sandy clay loam | Pusa Basmati 1 | 4700 | 4500 | Van Quyen and Sharma (2003) |
| Vermicompost | Vermicompost applied N equivalent basis (100% N). Additionally Supplied 28 kg $P_2O_5$ and 70 kg $K_2O$. | N:P:K 80: 26:42 kg $ha^{-1}$ | Lateritic soils | Pusa Basmati | 3400 | 3200 | Bhadoria et al. (2003) |
| Wheat straw | Wheat straw @ 5 t $ha^{-1}$, to meet 100% N of recommended fertilizer dose. | $N:P_2O_5:K_2O$ 80:40:30 kg $ha^{-1}$ | Fine loam | Akashi | 1567 | 2157 | Sarkar et al. (2003) |
| Winter weeds | Weed manures incorporated 15 days prior to transplanting of rice. | $N:P_2O_5:K_2O$ 120:60:40 kg $ha^{-1}$ | Silty clay loam | RP-3392-79-45-18-8 | 3870 | 4000 | Saha et al. (2007) |

approach that harnesses nutrient sources like crop residues, organic manure and soil biological activity and accommodates legume crops in rotation and biological N fixation etc.

Fortunately, rice ecosystem offers an appropriate environment and potential organic amendments, and also, the biofertilzers adequately supply the plant nutrients. Since the nutrient release pattern of these organic amendments varies greatly (Shiga et al. 1985), critical growth/development stages deserve attention in order to avoid plant nutrient stress. Organic manures having C:N ratio less than 15:1 like poultry manure, vermicompost mineralize rapidly in soil and manifest effects that are almost similar to mineral fertilizers (Sistani et al. 2008; Olesen et al. 2009). Given the critical importance of N in organic management, split application of highly mineralizable N-rich organic amendments like vermicompost, oil–cake pallets and poultry manure can be performed at sensitive growth stages.

The rate of organic nutrient input is primarily calculated on the basis of N equivalent rate (Murmu et al. 2013). A huge quantity of basic organic amendments (FYM, vermicompost, crop residues and farm compost) thus needed is often difficult to arrange at farm level. The effectiveness of green manure (Van Quyen and Sharma 2003) and legume-based crop rotation as plant nutrient source are well established in rice production. Leguminous green-manure crops can supply up to 30–50% of the N needs of rice varieties (Preston 2003); additionally, it improves soil carbon and weed management along with putting breaks on cereal disease cycles (Bowcher and Condon 2004). According to Stockdale et al. (2001), a well-designed crop rotation is central to the success of organic production systems. Leguminous crops in rotation with rice leave significant residual N, which eventually can lessen the external nutrient requirement for rice crop.

Concerning biofertilizers, a wide range exists including blue green algae (BGA), *Azolla*, *Rhizobium*, *Azotobacter*, *Azospirillum*, *Acetobacter* and phosphate solubilizing microorganisms (PSMs), which can be used for N or P nutrition in organic rice production system. Among these, *Azolla* decomposes rapidly, thus instantly providing N to rice (Raja et al. 2012); and an average increase in rice yield up to 1.4–1.5 t $ha^{-1}$ could be achieved through effective inoculation of *Azolla* (Mian 2002; Ciss and Vlek 2003). Similarly, *Herbaspirillum* is an endophytic diazotroph, which colonizes in rice roots (Baldani et al. 1986), and can fix 31–54% of total rice plant Ndfa under gnotobiotic conditions (Baldani et al.

**Table 2** Relative effectiveness of integrated application of organic amendments in rice

| Organic source/s | Quantity (ha) | Inorganic fertilizer rate | Soil type | Rice variety | Grain yield (kg ha$^{-1}$) | | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | Organic | Inorganic | |
| *Azola* + blue green algae (BGA) + FYM | BGA@ 15 kg ha$^{-1}$, *Azolla* @ 1.0 t ha$^{-1}$, FYM @ 5.0 t ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 80:40:40 kg ha$^{-1}$ | Silty clay loam | Pusa Basmati 1 | 3660 | 4380 | Singh et al. (2007) |
| Azola + BGA + FYM + Vermicompost | BGA@ kg ha$^{-1}$, *Azolla* @1.0 t ha$^{-1}$, FYM and Vermicompost @ 5.0 t ha$^{-1}$ | N:$P_2O_5$:$K_2O$ 80:40:40 kg ha$^{-1}$ | Silty clay loam | Pusa Basmati 1 | 4050 | 4380 | Singh et al. (2007) |
| Biodigested slurry + *Azospirillum* | 50% N through biodigested slurry | N:$P_2O_5$:$K_2O$ 100:50:50 kg ha$^{-1}$ | Clay | ADT 38 | 5980 | 5570 | Jeyabal and Kuppuswamy (2001) |
| FYM + Sesbania green manure + BGA+ phosphate solublizing bacteria (PSB) | PSB was inoculated by dipping the roots of rice seedlings in the slurry of *Pseudomonas striata* culture. | N:P:K 180:39:51 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 5200 | 4500 | van Quyen and Sharma (2003) |
| FYM+ SGM + BGA | FYM @ 10 t ha$^{-1}$ | N:P:K 180:39:51 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 4900 | 4500 | van Quyen and Sharma (2003) |
| FYM + *Azospirillum* + phosphobacteria | 50% N through FYM | N:$P_2O_5$:$K_2O$ 100:50:50 kg ha$^{-1}$ | Clay | ADT 38 | 5950 | 5570 | Jeyabal and Kuppuswamy (2001) |
| FYM + BGA | FYM @ 10 t ha$^{-1}$ at the time of final puddling; BGA was inoculated 10 days after transplanted | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 4240 | 4470 | Nguyen Van et al. (2002) |
| FYM + green manure | FYM @ 5 t ha$^{-1}$; Daincha was grown for 48 days and was incorporated 5 days before transplanted. | Compared with control | Clay loam | White Ponni | 3975 | 2150 | Deshpande and Devasenapathy (2010) |
| FYM + green manure (GM) + BGA + PSB | FYM @ 10 t ha$^{-1}$ at the time of final puddling; *Sesbania* was grown for 60 days and was incorporated 5 days before transplanted ; BGA was inoculated 10 days after transplanted, PSB was inoculated by dipping the roots of rice seedling in the slurry of PSB culture. | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 5150 | 4470 | Nguyen Van et al. (2002) |
| FYM + microbial culture (MC) | The organic sources supplied the nutrient input equivalent to | N:P:K 80:26:42 kg ha$^{-1}$ | Lateritic soil | Pusa Basmati | 3600 | 3200 | Bhadoria et al. (2003) |

**Table 2** (continued)

| Organic source/s | Quantity (ha) | Inorganic fertilizer rate | Soil type | Rice variety | Grain yield (kg ha$^{-1}$) | | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | Organic | Inorganic | |
| | 80 kg N 47 kg $P_2O_5$ and 84 kg $K_2O$ per hectare | | | | | | |
| FYM + GM | FYM @ 10 t ha$^{-1}$ at the time of final puddling; *Sesbania* was grown for 60 days and was incorporated 5 days before transplanted. | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 4790 | 4470 | Nguyen Van et al. (2002) |
| GM + FYM + BGA | FYM @ 10 t ha$^{-1}$ at the time of final puddling; *Sesbania* was grown for 60 days and was incorporated 5 days before transplanted ; BGA was inoculated 10 days after transplanted. | N:$P_2O_5$:$K_2O$ 120:60:40 kg ha$^{-1}$ | Sandy clay loam | Pusa Basmati 1 | 4910 | 4470 | Nguyen Van et al. (2002) |
| GM + FYM | GM @ 22.5 t ha$^{-1}$ + FYM @ 22.5 t ha$^{-1}$ | N:P:K 160:16.4:100 kg ha$^{-1}$ | Silty loam | - | ~8350 | ~8050 | Liu et al. (2009) |
| Poultry manure (PM) + GM | GM @ 3.5 t ha$^{-1}$, Daincha was grown for 48 days and was incorporated 5 days before transplanted. | Compared with control | clay loam | White Ponni | 4844 | 2150 | Deshpande and Devasenapathy (2010) |
| Vermicompost + GM | Vermicompost @ 4 t ha$^{-1}$; Daincha was grown for 48 days and was incorporated 5 days before transplanted. | Compared with control | clay loam | White Ponni | 4774 | 2150 | Deshpande and Devasenapathy (2010) |
| Vermicompost + *Azospirillum* + phosphobacteria | 50% N through vermicompost | N:$P_2O_5$:$K_2O$ 100:50:50 kg/ha | Clay; *Udic chromustert* | ADT 38 | 6250 | 5570 | Jeyabal and Kuppuswamy (2001) |

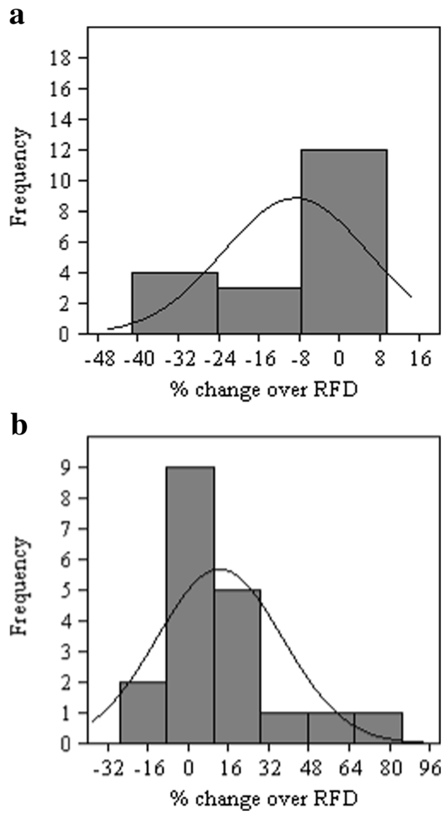

**Fig. 2.** Frequency distribution of changes in rice grain yield under organic nutrient management (**a** sole component of organic nutrient input, **b** integrated application of different organic nutrient input/biofertilizers) as compared to recommended ferlizer dose (RFD)

2000). Also, *Burkholderia* species, e.g., *Burkholderia kururiensis*, *Burkholderia tuberum* and *Burkholderia phynatum*, hold potential of fixing N$_2$ (Estrada-de los Santos et al. 2001; Vandamme et al. 2002) and its inoculation can increase grain yield in the range of 0.5–0.8 t ha$^{-1}$ (13–22% increase) (Tran Van et al. 2000). Recently, a *Rhizobium* strain has been demonstrated to infect rice–roots, travel upward to stem and growing leaves and improve its growth (Chi et al. 2005). Extensive research is required in this direction so that input requirement from diverse sources could be optimized and potential of crop rotation and bio-fertilizers could be realized for organic rice production.

## Quality of organic rice

Rice grain quality constitutes the prime concern with regard to the export standards in international market (Saha et al. 2007). At present time, basmati and fine grain aromatic rice hold tremendous export value, and hence, quality standards remain vital for harnessing the global organic rice market. Usually, organic produce is considered healthier, safer and tastier than the conventional (chemical) farm produce (Stockdale et al. 2001). Research has shown that organic management can improve quality (higher vitamins and nutrients) for fruit and vegetable crops and also helps minimize the toxic chemical load (Lairon 2010). Few researchers have concluded that the organic production improves the quality of rice (Bourn and Prescott 2002; van Quyen and Sharma 2003; Saha et al. 2007), while others have failed to establish any significant change in quality parameters. Given this, conclusive evidences highlighting the differences in the quality of rice grain under organic- and chemical-based farming still need to be furnished.

By definition, rice grain quality is evaluated based on four parameters viz. milling, cooking, appearance and nutritional quality (Li et al. 2003). With adoption of organic management in rice, major changes are observed in the grain protein content. In general, organic rice is low in protein content than conventionally grown rice crop (Worthington 2001; Magkos et al. 2003). For instance, Saha et al. (2007) reported 13.4% reduction in grain protein inorganic practices (FYM applied at 10 t ha$^{-1}$) compared to inorganic fertilization (100:60:40 kg NPK ha$^{-1}$). The reduction in grain protein content of organic rice is associated with limited N availability that curtails the uptake of N, thereby negatively impacting upon protein synthesis (Champagne et al. 2007). Besides, Dangour et al. (2009) found that increased availability of silica in organic paddies also restricts the N accumulation in rice grain. Protein content is also known to influence the cooking quality of rice due to former's negative correlations with slickness and stickiness, and a positive correlation with roughness (Champagne et al. 2007). Though low protein organic rice turns softer after cooking and is normally preferred over high protein conventionally grown rice (Primo et al. 1962; Tamaki et al. 1989; Kaur et al. 2015), the palatability of organic rice is generally low given its reduced protein content. Additionally, the low-protein rice also has higher organoleptic qualities (flavour) (Juliano et al. 1965; Champagne et al. 2009; Kesarwani et al. 2016). Further, organic rice becomes sticky after cooking due to an increase in viscosity and breakdown values and thus has better eating quality (Champagne et al. 2007). Significant reduction in grain amylose content in organic rice has also been reported (Kaur et al. 2015; Huang et al. 2016). After cooking, organic rice generally has lower gruel solid loss and higher elongation and width expansion ratio (Kaur et al. 2015).

For other grain nutrients, very low degree of variation is observed with majority of reports documenting inconsistent results. Champagne et al. (2007) have suggested that the content of major nutrients (NPK) in rice grain got reduced with the duration of organic farming in contrast to the Mg content that increased gradually with time. Likewise, Nakagawa et al. (2000) have documented that the organic rice had higher Zn, and lower N, K and Ca contents than that of conventionally grown rice. The elemental composition of organic rice is quite different from that of conventionally grown rice. More recently, quadrupole inductively coupled plasma mass spectrometry (q–ICP–MS) employed to classify organic and conventional rice with 96–98% accuracy based on 19 elements (Barbosa et al. 2016). Organic rice contains higher concentration of P, Zn, Cu, Mn, Co, Cr, As, B and Ba and less concentration of Ca, K, Rb, Mo and Se as compared to ordinary rice (Borges et al. 2015). Also, milled organic rice exhibits significantly higher length/breadth (L/B) ratio and kernel weight but has low bulk density as compared to conventional rice (Kaur et al. 2015). In general, physical grain quality as assessed using parameters such as head rice recovery (HRR), milling and hulling percentage and L/B ratio does not show variations in short-term organic farming. However, organic methods of rice cultivation help to improve the physical grain quality in the longer run (Surekha et al. 2010). In addition, rice pasting properties like setback value, peak viscosity and pasting temperature are deemed to improve under organic farming (Kesarwani et al. 2016).

The exclusion of synthetic fertilizers, pesticides and fungicides in organic rice cultivation often enhances the possibilities of fungal proliferation and mycotoxin production. For instance, 30% more incidence of OTA (Ochra Toxin—a mycotoxin) was reported in organic rice in comparison to the conventional rice products, which deteriorated the quality of the organic rice (Gonzalez et al. 2006). To offer a comprehensive understanding of the organic rice quality, detailed information on grain quality parameters particularly changes in levels of vitamins and toxic compounds and sanitary parameters is required in both short- and long-term experiments.

## A need for organic-responsive genotypes

Similar to conventional farming, selection of a suitable variety is also of paramount importance in organic farming. Notwithstanding the poor responsiveness of recent HYVs to organic inputs, organic farmers rely heavily on these varieties that also demand greater inputs including chemical fertilizer, pesticides, etc. (Lammerts van Bueren et al. 2002). According to Lammerts van Bueren et al. (2011), current organic cultivation worldwide is largely driven by the cultivars developed using traditional breeding protocols, which by virtue of the selection criterion tend to be high-input responsive. Non-availability of rice variety/genotype specifically bred for organic farming is the major limitation to realize the potential productivity. Hence, organic responsive rice varieties able to excel in low input condition are urgently needed to popularize organic rice production (Murphy et al. 2007; Wolfe et al. 2008). In fact, inclusion of semi-dwarf genes in cereals including rice greatly reduced the varietal efficiency of nutrient use (NUE), weed aggressiveness, depth of root systems and resistance to diseases (Verma et al. 2005; Cooper et al. 2006; Lueck et al. 2006; Klahr et al. 2007; Makepeace et al. 2007; Dawson et al. 2008; Hoad et al. 2008; Löschenberger et al. 2008; Lammerts van Bueren et al. 2011), the traits that align extremely well with the principal of organic production system. The specific plant traits (ideotypes) relevant to organic farming include low-input requirement, higher weed competiveness, yield stability, deep root system, ability to form active mycorrhizal associations and to maintain a high mineralization activity in the rhizosphere via root exudates, and associated ability to recover N leached from the topsoil (Lammerts van Bueren et al. 2002). The NUE is also a pivotal factor that determines the production potential under organic system. Agronomic NUE and N recovery efficiency of rice crop are significantly low under organic production system (Huang et al. 2016). Under low-input organic system, inability of HYVs to extract sufficient soil nutrients for the plant growth is often reflected as poor productivity level. In this context, Foulkes et al. (1998) opined that the varieties bred before and during 1960s tended to be more N-efficient than the HYVs bred under higher N level. As advocated by Huang et al. (2016), the selection of varieties for organic farming could preferably be made under low-input organic condition. Since the disease pressure is often low in organic farming due to ample rotation and low N input, employment of tolerant class or merely the field resistance can serve the purpose (Lammerts van Bueren et al. 2002). It can be inferred from Tables 1 and 2 that the basmati and superfine rice varieties are more responsive to organic farming as compared to conventional HYVs. The traits like weed aggressiveness that have received meagre attention from the crop breeders emerge as important when viewed from the context of organic agriculture.

## Pest dynamics and management options

In comparison to chemical-based conventional farming, organic farms usually have greater biological diversity, which favours diverse biological communities including insect pests, natural enemies and weeds (Hole et al. 2005). The intensity of pest pressure is seen as a potent yield-determining factor in case of organic rice production. Though application of pesticides may reduce the pest pressure at critical periods in conventional farming, availability of such measures that immediately put a check on pest population is meagre in organic production practices. According to the Organic Farming Research Foundation (OFRF) survey, the US-based organic farmers consider weed management as among top priorities in research needs (Walz 1999). Weeds pose a key problem in herbicide-restricted organic farming system (Hokazono and Hayashi 2012) and are considered as the second most yield limiting factor after reduced soil N availability under organic production. Barnyard grass (*Echinochloa* spp.) exemplifies this in organic rice production in New South Wales zone of Australia (Neeson 2005). Basically, low soil available N level intensifies the weed competitiveness (Lundkvist et al. 2008) and the problem often exacerbates with progressive development of weed seed bank in the long run (Lammerts van Bueren et al. 2002).

As a control measure, combination of cultural techniques comprising direct mechanical and thermal methods (Lampkin 1994; Stockdale et al. 2001) could be effective in controlling weeds. In Japan, organic rice yield is severely reduced due to a troublesome broadleaf weed *Monochoria vaginalis* and combined use of *Azolla* and Loach fish (*Misgurnus anguillicaudatus*) could improve rice yield via efficiently suppressing *M. vaginalis* (Cheng et al. 2015). Other potential strategies include appropriate crop rotation, timely water management and precision-levelled fields to ensure uniform flooding depth (floods up to 4 in to drown weeds). Mechanical weeding through power weeder and cono weeder can also be used for controlling weeds in rice fields.

Mostly, insect and disease severity is relatively less under organic rice. Organic farming can effectively suppress the soil-borne diseases with higher addition of organic manures that in turn improves overall properties of the soil (van Bruggen et al. 2016). Improved soil quality and enhanced microbial activity and slower growth rate facilitate chemical defences in plant that prevent most diseases and pest (Birkhofer et al. 2008). Moreover, enriched biodiversity harbouring increased population of antagonistic and beneficial microbes and natural enemies also underpins crop resistance against insects and diseases (Wilson et al. 2008; Meyling and Hajek 2010; Amano et al. 2011; Kitazawa et al. 2011). Importantly, organic agriculture leads to species richness and abundance of predatory invertebrates (Fuller et al. 2005; Hole et al. 2005; Smith et al. 2010).

In view of the above, deeper understanding of the crop–pest dynamics in organic rice production system will be instrumental in devising pest management strategies that are compatible with the concept of organic agriculture. Based on a comparative analysis, Kajimura et al. (1993a) concluded that the population densities of the brown plant hopper (*Nilaparvata lugens* Sthl) and the white-backed plant hopper (*Sogatella furcifera* Horvfith) were observed to be much lower in an organically grown rice field. In other studies, lower density of the plant hoppers could be attributed partly to an unfavourable nutritional status (low N content in the organic rice plants) (Kajimura et al. 1995) and lower density of rice stems in the early season in the organically farmed field (Kajimura et al. 1993b). Similarly, the nymphs of rice grasshopper (*Oxya japonica* Thunberg) grew slowly in organic rice soil and conventional as N-rich and C-poor conventional rice plants facilitate higher multiplication of this herbivore (Butler et al. 2012; Trisnawati et al. 2015). This study suggested that modifying fertilization regime could help manage insect pest population. However, some insect pests emerge with enhanced aggressiveness under organic rice cultivation. Examples include burgeoning infestation problem of mirid bug (*Stenotus rubrovittatus*) in Japan that resulted in increased economic losses for organic rice farmers (Takada et al. 2012). Importantly, since the quality of rice depends on its appearance, the bug incidence even at very low intensity causes severe economic damage through creating black spots on rice grains (pecky rice) (Tindall et al. 2005; Kiritani 2007). Fortunately, *Tetragnathidae* and *Lycosidae* spiders were identified as potential natural enemy that frequently feed on these bugs in organic rice fields (Kobayashi et al. 2011). The use of such bio-agents therefore could be an integral part allowing successful pest management under organic rice. Bio-agents like *Trichogramma japonicum* and *Trichogramma chilonis* are effective against stem borer and leaf folder (Jain and Bhargava 2007); likewise, *Trichoderma viride* and *Trichoderma harzianum* control blast disease in rice; *Pseudomonas aeruginosa* and *Pseudomonas putida* reduce sheath blight infection (*Rhizoctonia solani*) in rice; arbuscular myorrhizal (AM) fungal to minimize sheath blight (ShB) disease incidence. Excessive N levels predispose rice plants to a variety of disease including sheath blight and kernel smut. Organic crop management practices that promote microbial population feeding on nematodes thus cause a reduction in the relative abundance of plant parasitic nematodes (Surekha et al. 2010). The potential of natural bio-pesticides further needs to be carefully examined under organic rice farming. To this end, recent study reported reduction in Gundhi bug population (*Leptocoryza varicornis*) by means of foliar application of vermiwash, neem oil followed by aqueous garlic and annona leaf extract (Mishra et al. 2015). This implies towards implementation of an integrated approach to efficiently control the pest pressure in organic rice farming.

## Environmental and ecological issues

Environmental and ecological issues remain pertinent to twenty-first century agriculture in the face of climate change, and organic farming by its very nature is considered to be more environmental friendly. On the flip side, application of amendments from organic sources in a typical flooded rice ecosystem enhances the emission of greenhouse gases (GHG), $CH_4$ in particular (Crutzen 1995; Houghton et al. 1995). With higher global warming potential (21 times $CO_2$ eq.), $CH_4$ is largely responsible for global warming (IPCC 2007) and flooded rice contributes almost 19% of the total agricultural $CH_4$ emission worldwide (US–EPA 2006). However, organic paddy farming causes substantially lower $N_2O$–N emission than conventional paddy farming (Rahmawati et al. 2015) and efficient water management can further reduce $N_2O$–N emission.

Organic rice production emits $CH_4$ at a rate that is 20% higher than the conventional system (Qin et al. 2010). Researchers have quantified the global warming potential of conventional rice (1.46 kg $CO_2$ eq. $kg^{-1}$ rice) and organic rice (2.0 kg $CO_2$ eq. $kg^{-1}$ rice) (Hokazono and Hayashi 2012), and notably higher values have been reported in case of organic rice production. Among the crucial players, higher addition of organic matter is instrumental in direct and indirect emission of GHGs from organic rice field as decomposed organic matter serves as methanogenic substrate (Zheng et al. 2007). The emission rate of GHGs particularly $CH_4$ is further inflated by application of dehydrated and palletized manure (Qin et al. 2010) and the crop residues having higher C:N ratio. A multi-location field experiment in Japan showed up to 3.5-fold more $CH_4$ emission when rice straw was added at the rate of 6–9 t $ha^{-1}$ (Yagi and Minami 1990). According to a recent study by Datta et al. (2013), cumulative seasonal $CH_4$ flux (kg $CH_4$ $ha^{-1}$) during the wet season quantified for different organic nutrient sources manifested the following order: farmyard manure (FYM) (175.03) > dhaincha (130.99) > control (123.87) > morning glory (119.51). Several researchers have reported an increase in $CH_4$ emission from rice field with the application of FYM (Debnath et al. 1996; Amon et al. 2001; Pathak et al. 2003), especially when FYM contains significant amount of pig manure (Møller et al. 2004). Therefore, either use of FYM should be allowed to a certain limit or proper decomposition of FYM should be ensured ahead of applying it in organic rice farming.

Besides this, time of application also influences the emission rate to a large extent. Research results suggest that the conversion factor was ~1.0 for straw incorporated shortly [less than 30 days] before cultivation, and it reduced drastically (0.29) when straw was incorporated long before [more than 30 days] cultivation (IPCC 2006). On the other hand, the conversion factor was usually low (~0.05) for well-decomposed compost (IPCC 2006). Thus, proper decomposition of organic amendments and their incorporation well before cultivation should be encouraged to enable minimization of GHGs emission.

Organic systems add more organic amendments, but adding amendments in times of drainage could avoid higher GHGs emissions (Xu et al. 2000; Cai and Xu 2004). Midseason drainage appears to be an effective option to mitigate the net GWP from rice fields, especially when larger amounts of rice straw are returned into the soil (Nelson 2009). However, mid-season drainage substantially increases $N_2O$ emissions in both conventional and organic rice production systems (Gathorne-Hardy 2013). One potential approach could be the integration of organic practices with resource conserving system like SRI method of rice cultivation where soils are kept un-flooded most of the growing period and hence $CH_4$ emissions are significantly reduced (Dobermann 2004; Stoop and Kassam 2005; Gathorne-Hardy 2013).

Apart from issues described above, using pesticides in conventional paddy production can inhibit the methanogenesis process (Gathorne-Hardy 2013). For instance, insecticides like carbofuran and endosulfan minimize $CH_4$ production (Kumaraswamy et al. 1998; Bharati et al. 1999). Restricted use of these pesticides in organic rice farming renders this system unable to harness pesticide-enabled suppression on $CH_4$ emission. By contrast, some herbicides are reported to increase $N_2O$ emissions under conventional rice paddies (Das et al. 2011), thus offering a potential 'climate plus' for organic rice production. The information on GHGs emission is however limited for newly emerging pesticide molecules in rice fields. Thus, effective organic management practices conductive to climate mitigation in rice based production system should be explored.

## Future prospects and research needs

Concentrated research efforts are essentially needed to develop more location-specific crop management strategies in order to promote larger-scale organic rice farming. This calls for ecosystem-based knowledge and skills to be applied (Stockdale et al. 2001). Future research activity should certainly focus onto improve plant nutrition particularly N accessibility, NUE and synchronous supply of plant nutrients through integrated use of diverse organic nutrient sources. Equally important will be the deployment of rice varieties more relevant to organic rice cultivation that are low input demanding, organic responsive and hold resistance to major diseases and insect pests. Comprehensive study on crop–weed ecology remains crucial to allow strategic weed control (Stockdale et al. 2001). Soil solarization and anaerobic soil disinfestations (addition of fresh organic material in moist soil and covering with plastics for three to six weeks) might be useful in controlling weed and soil borne diseases that should be explored (van Bruggen et al. 2016). Growing environments and production ecology largely impact the performance of organic rice. To this end, identification of favourable eco-zones will be useful in advancing organic rice as a profitable farming system.

In the face of declining water resources, water saving also emerges as a major concern in rice production (Hazra and Chandra 2016) which causes agriculturists to incline more towards aerobic rice production. Non-flooded aerobic rice and organic rice farming could be effectively combined given their practical complementarity. Addition of organic matter helps to improve water retention capacity in aerobic rice soil. Further, aerobic rice system offers potential solution for reduced N mineralization and emission of GHGs. Along these lines, SRI and other non-flooded aerobic rice cultivation methods could be promising options to popularize organic rice (Alam 2015). Majority of the experiments reported in literature so far are confined to short-term evaluation of organic management on rice productivity. Long-term research investments on organic rice production system should be in place in order to precisely evaluate the relative annual rate of additive functions in organic rice. In conjunction, an emphasis should be placed on nutrient dynamics, disease, pest and weed seed bank under long-term organic rice system which may directly influence the performance potential of organic rice.

Strategically designed crop rotations stand at the core of pest management approach in organic agriculture systems (Lotter 2003). Responsiveness of legume/pulse crops to organic farming make rice–legume/pulses rotations like rice–rice, rice–lentil/chickpea/pea and rice–rice–dhaincha/sunhemp/cowpea promising choices. Likewise, organic rice–duck farming was found profitable, eco-friendly and less energy intensive (Li et al. 2012). Adoption of organic farming in a co-operative mode at farm level similar to what is being practiced in Hondongs, South Korea (Suh 2015), is likely to provide a great impetus to organic farming especially in rice growing areas of Asia.

## Conclusion

In this review, we illustrate that the existing organic rice production faces an array of constraints. The present understanding of organic rice system is relatively poor and this area has not attracted adequate research investments. Based on the constraint analysis, a renewed focus is essential towards the previously unexplored aspects like development of organic responsive variety, strategic N supply system and integrated management of the biotic factors and most importantly to bring down the GHGs emission. Next-generation breeding techniques especially those dealing with crop 'rewilding' need to be carefully accommodated within the framework of organic agriculture to improve the productivity of organic system, though [as reviewed by Andersen et al. (2015)] this represents a herculean challenge necessitating a dramatic change not only in the government policies but also in the mindset of farmers and consumers. Some of the potential crop management strategies like efficient crop rotation, aerobic rice cultivation and integrated nutrient management including split application of nutrient dense manures need to be carefully evaluated in future to improve the productivity of organic rice system. In parallel, attempts should be made to elucidate nutrient dynamics, monitoring the pest complex and quality parameters to better characterize the organic rice production system. Given the growing concern against chemical-based farming, organic rice holds promise to attain food security and environmental sustainability worldwide.

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