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REVIEW ARTICLE

Crop improvement strategies for mitigation of methane emissions from rice

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ABSTRACT

Climate change and its effects on agriculture will impact global food security. Rice (*Oryza sativa* L.), the major staple crop of the world, is subjected to substantial environmental constraints and criticism because of its role in climate change; methane emission under irrigated ecosystem. Mitigation of methane is the way forward for sustainable and eco-friendly rice production. Limiting area and production of rice may not be a feasible option as majority of the Asian population depends on rice. An urgent and integrated research approach to understand the mechanisms and interactions involved in methane release through rice plant is required to design viable mitigation technologies. Genetics of methane emission must be studied in detail, along with agronomic and management practices to obtain the precise information to elucidate the inheritance of related traits. Crop improvement interventions are required to identify contributing traits to methane emission, with subsequent deployment in plant breeding. Identification of rice cultivars with high-yield levels and traits contributing to low methane production represents an economic approach. Focus of breeding needs a shift towards adaptation to new production systems that can sustain effects of climate change. Low methane emitting varieties suitable to water management practices are more promising. This can be manifested in simultaneous achievement of global food security and mitigation of emissions without radical changes in the agronomic practices for the rice ecosystem. In this Review, an account of methane emission studies from rice and impact of crop growth stages as well as traits are outlined. The genotypic variation reported in *Oryza* spp for methane emission and breeding approaches for development of low methane emitting varieties are discussed.

Keywords: Crop improvement; Genotypic variation; Methane; Mitigation; Rice

INTRODUCTION

Evidence of imminent climate change is undeniable. An increasing drift in Global Mean Surface Temperature (GMST) was quite obvious after 2000 as it is recorded that each decade is warmer than its preceding one. The global maximum and minimum temperature have increased since 1951 (IPCC 2013) and increasing concentrations of the greenhouse gases are the significant indicators of global warming and climate change (Denman et al. 2007). Agriculture and climate change have significant impacts on each other. The latent effects of climate change on agriculture have motivated international research towards this direction (Aydinalp and Cresser 2008). The phenomenon of greenhouse effect is natural and necessary to support life on earth; however frequent extreme weather conditions, increased greenhouse gases in the atmosphere are affecting the ecosystems adversely (EPA 2012). Change in climate, results in the alteration of vegetation type, distribution and coverage. Shift in regional precipitation and warmth has profound effects on plant growth and development. Global warming and augmented CO_2 concentration together result in high productivity due to increased photosynthesis (Jagadish et al. 2007; Gerardeaux et al. 2012). However, in spite of these beneficial effects, combination of elevated temperature with unpredictable precipitation would negatively influence food production. Changes in temperature will result in early flowering and fruiting and in reverse, cold temperatures will leads to slow down of bio cycles of organisms (Porter and Semnov, 2005). It was reported that there was a 1% decline in global net agricultural production during 2000 to 2009 compared to a 6% increase in the previous decade (1982 to 1999). A reduction of 10-40% in crop production is predicted for Indian subcontinent by 2080-2100 due to temperature variations (Aggarwal 2008).

About 20% of the yearly contribution of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) gas

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emissions is from agriculture sector (IPCC 2007). Methane has high global warming potential, 25 times than that of CO_2 and it also absorbs more energy than CO_2. CH_4 is a precursor of ozone, which is another important greenhouse gas. The mean global CH_4 concentration in the atmosphere in January, 2016 was 1842.3 ppm which increased to 1851.4 ppm in January, 2017 (Dlugokencky, NOAA/ESRL/www.esrl.noaa.gov/gmd/ccgg/trends_ch4/). Major contributors of methane from agriculture are inundated rice fields, crop residue burning, livestock rearing and allied manure management. Methane emissions from paddy fields were reported in 1913 by Harrison and Aiyer, but comprehensive studies were conducted after 1913 (Cicerone and Shetter 1981; Seiler et al., 1984; Holzapfel-Pschorn et al., 1985; Schutz et al., 1989; Bayer et al., 2014; Mendelsohn 2014; Tang et al., 2015; Han et al., 2016; Brye et al., 2016). Previous reports show an urgent need to design strategies for methane mitigation and detection of suitable cropping patterns and genotypes for the vulnerable areas. In this paper we discuss methane emission mitigation strategies with a special focus on the role of genotypic improvement.

Rice and climate change

Rice has been playing major role in global food security since time immemorial (Biswajit et al., 2013; Mohanty et al., 2013). More than 114 countries produce rice (FAO 2013) in diverse ecosystems and in the widest range of altitudes and latitudes across the globe (Nguyen 2005). Rice crop with no limitation in its growing conditions survived centuries over adverse conditions and number of biotic and abiotic stresses. Significant improvement in the production, area under cultivation and consumption was observed in the last century due to its wide genetic diversity, adaptation and accelerated evolution by a large international community of researchers dedicated to this single crop.

Climate change has serious impact on rice production and, consecutively, rice fields are contributing to global warming through methane emissions. There will be a predicted positive influence of climate change on rice production in specific areas of temperate regions of northern hemisphere but overall negative effect on the global net production. The global warming effects like frequent droughts, higher temperatures, flooding, salinity, increased carbon dioxide levels, rise in sea-level, irregular rainfall patterns and shifting of pest dynamics has been found to contribute negatively to rice production. Research studies at IRRI, Philippines indicated that a rise in $1^{O}C$ night temperature cause 10% reduction in rice yield. Increased atmospheric CO_2 and 1degree rise in temperature have been shown to increase GHG intensity by 31.4% and 11.8% respectively and decreases rice yield (van Groenigen et al., 2013). Global mean crop yields of major staple food crops including rice are predicted to decline from 3-10% per degree of temperature rise above historical levels (Challinor et al., 2014). As a result of climate change, decline in rice yields to a level of 15% and a subsequent 12% increase in rice prices, is forecasted by International Food Policy Research Institute (IFPRI) by 2050 in developing countries while the rice production is expected to increase to feed the ever-growing global population. IFPRI, 2010 forecasted a 31.2% price hike for rice even in the optimistic scenario from 2010 to 2050 with a detrimental effect on global food security. Reduction in 48.63% of land productivity by the year 2100 was estimated by Kumar et al., 2016, based on simulation techniques considering the effects of climate change. In Asia, where rice is grown in a comparatively larger area and is the primary food of majority, adverse production and accessibility will cause major food scarcities.

Being a crop which is grown majorly in irrigated flooded ecosystem, rice is mainly criticised for two interrelated components contributing to climate change, i.e. methane emissions and low water productivity. The methane emissions in rice field depend on various factors like cultivars, microorganisms in the root zone, soil under cultivation and other agricultural practices like water management, manure and fertilizer application. CH_4 production in rice fields is also contributed by decaying plant-borne tissues and root exudates in the anaerobic conditions. It was reported that, transport of over 90% of methane to the atmosphere, is through rice plants (Banker et al., 1995). During the production of 1 kg of rice grain, 100 g of methane is emitted. The default methane baseline emission factor is 1.3 kg CH_4 $ha^{-1\ day-1}$, in continuous flooding rice cultivation (IPCC, 2006). However, Pathak (2015) reported that the methane emissions from Indian rice field had remained almost constant from 1970 to 2010, though the total rice production had increased from 115 to 128 Mt during the same period.

Adapting to climate change, there is a demand to substitute rice with crops having minimal water requirement. Even a gradual replacement of rice will have detrimental impacts on social, cultural, economic and political scenarios, especially in south Asian countries. Conversely, rice consumption was increased in non-traditional areas outside Asia and displaced major staple food crops in Africa in the last few decades (Mohanty et al., 2013). Even though, there is much focus and concentrated efforts are made for breeding climate smart rice to cope up with alarming conditions of drought and temperature, there are only limited studies available for genetic enhancement to mitigate methane emission.

Combining adaptation and mitigation strategies is a way forward to meet future food security goals while minimizing further impacts on climate change and emissions due to food production (Campbell et al., 2016). Numerous studies on effect of various agronomic and management practices to mitigate methane emissions from paddy fields are reported. Malyan et al., 2016 reviewed influencing factors and basic strategies for methane mitigation in paddy cultivation and concluded that breeding for improved rice varieties with low CH_4 emission is a potential mitigation option. Radical changes in crop management without considering the genotypic effect may be detrimental in meeting global food demands. As methane emission is contributed by interactions of genotype, microorganisms, water and soil conditions; independent analysis of these factors for emission may result in biased estimates. Future studies have to be focused more on understanding the mechanisms and interactions of various factors and their actual contribution to the methane emissions. As it is evident from the role of plant breeding in green revolution and global food security, there is a need of crop improvement interventions in the problems of global climate change along with crop production and management practices for significant outcome. As a direct option, the genotypic/varietal differences in methane emission should be explored on a large scale. The morphological, physiological and microbiological factors also need to be dissected and utilized in crop improvement. It is necessary to breed high yielding rice varieties with reduced green house gas emissions, which are adaptable to the essential soil and water management conditions.

Methane emissions from rice field

Rice cultivation plays a major role in global warming by green house gas emissions (Neue, H. 1993; Sass and Cicerone 2002; Jain et al., 2004; Linquist et al., 2012; Gaihre et al., 2013; Pittelkow et al., 2013). Matthews et al., 1991, identified that 55% of the annual methane emission over rice growing areas is concentrated into four months, from July to October i.e. the predominant rice cultivation season. Even though the methane emission in paddy fields is influenced by various factors; genotypic variation contributed more and substantial differences up to 56% among cultivars (Gogoi et al., 2008). Deviation in methane efflux among rice cultivars from the paddy fields could be attributed from variability in gas transport potential, metabolic activity and plant architecture (Sigren et al., 1997; Huang et al., 1998). Ma et al., (2012), analysed emissions of different rice cultivars at seedling stage and reported that methane emission was affected by varietal traits and crop density. Rice cultivars show a range of variation for transport of oxygen and cause difference in redox potential at rice rhizosphere and, thereby, variation in methane oxidation (Flessa and Fisher, 1992; Kludze et al., 1993).

Significant variations were observed between rice fields growing different rice cultivars for methane emissions which could be ascribed to the deviations in their methane metabolic pathway (Kaushik and Baruah 2007, Lou et al., 2008; Ma et al., 2010). Wang et al., (1997) reported that rice plants affect the soil Eh value due to variation in root respiration and exudation amongst different cultivars which eventually influence methane production (Aulakh et al., 2001; Han et al., 2013). Gas conductance through aerenchyma and release of oxygen to the rhizosphere and methane to atmosphere, varies among rice cultivars and results in dissimilarity in emission potential (Aulakh et al., 2000; Mei et al., 2009; Li et al., 2013). Mitra et al., (1999), studied methane emission potential of six popular rice varieties under flooded conditions and results indicated that considerable variation exist between the varieties. The average methane emissions varied from 0.65 to 1.12 $mgm^{-2}h^{-1}$ and the maximum seasonal emission was observed in a variety Pusa 933 and minimum emission was observed in Pusa 169 ranging from 27.2 kg ha^{-1} to 15.6 kg ha^{-1} respectively. Shin and Yun (2000), studied methane emission amongst eight Korean cultivars under uniform field conditions and reported significant variation in the CH_4 flux rate between 36.7 (Dasanbyeo) to 76.0 g CH_4 m^{-2} (Mangeumbyeo).

Watanabe et al., 1995, compared the effect of rice cultivar on methane emission potential using hybrids, *indica* and *japonica* types. Although the hybrids produced more biomass than *indica* and *japonic*a types, the methane emission rates were analogous. However, Ma et al., 2010, reported as hybrid rice produced 50–60% more shoot biomass compared to cultivars and the emission rates were comparable to *japonica* and lesser than *indica*. The hybrid rice cultivars were showed variation in methane transport based on the difference in growth parameters and the anatomical characteristics like aerenchyma development. It was also observed that hybrid rice had a positive influence on the methanotrophic population around rhizosphere, which helps in reducing methane emission by enhancing oxidation of methane.

Effect of crop growth stages on CH_4 emission

The pathway for methane emission is routed from the soil to the atmosphere primarily through plant transportation system. During the crop duration, 90% of total methane emission is conducted through the plant and the conductance through water column is negligible. Gogoi et al., 2008, studied methane emission in different ecosystems using diverse rice cultivars. Methane peaks were observed at active tillering stage and reproductive stage of the crop. Tang et al., 2016, studied gas emissions during growth stages and showed highest peak of emissions at booting stage followed by tillering stage. Aerenchyma cells in the rhizosphere supports CH_4 transport during active tillering through diffusion mechanisms (Yu et al., 2016).

At active tillering stage, rice plant augments the passage of CH_4 produced in the root zone to the atmosphere (Gogoi et al., 2003; Bhattacharya et al., 2013; Suryavanshi et al., 2013; Miyata et al., 2000; Meijide et al., 2011; Alberto et al., 2014). The methane emission at reproductive stage entails almost to 90% (Cicerone and Shetter 1981; Schutz et al., 1989). During this stage, root exudates increase CH_4 production by supplying carbon resource and mobilizing micronutrients and methanogenic microorganisms (Denier et al., 1995; Ziska et al., 1998; Lu et al., 2009). Root exudates and decaying plant biomass also have potential influence on methane emission with enhanced production in the soil zones surrounding root system (Sass et al., 1992, Majumdar, 2003), especially for the CH_4 flux changes at panicle initiation stage (Bouwman 1991;Wassmann et al., 1993; Kruger et al., 2001 and Tokida et al., 2010). After the panicle development and grain filling, decline in the emission has been detected due to ageing and loss of permeability of root epidermis and conductance in the shoot (Nouchi et al., 1990; Wang and Patrick, 1995).Together with reduction in dissolved organic carbon at the end of crop growth stage methane emissions were observed to be declined drastically (Lu et al., 2000; Das et al., 2008).

Genotypic variation for methane emission

As rice plant is the source of substrate, site of methanogenesis and channel for the transfer of more than 90% of methane fluxes from irrigated field (Holzapfel-Pschorn et al., 1985; Jia and Cai 2003; Hussain et al., 2014), cultivar variation is the key factor that influences methane emission (Mosier et al., 1990; Fu et al., 2009; Su et al., 2015; Qin et al., 2015). The rice cultivars vary for the capacity to transport oxygen to the rhizosphere (Kludzeet al., 1993; Adhya et al., 1994; Mitra et al. 1999; Aulakh et al., 2000; Kumar and Viyol, 2009). Bahl et al., (1997) observed a difference of 24-31% in methane emissions between *japonica* cultivars for two consecutive years. Nugroho et al., (1997), screened 8 popular varieties in Indonesia and found Atomita-4 with lowest quantity of CH_4 released per kg of grain production. This trait is mainly influenced by grain yield of the cultivar and fertilizer applications to the field. Shin and Yun, 2000, found a cultivar Dasanbyeo with lowest CH_4 flux after screening popular Korean rice cultivars. Das and Baruah, 2008, found the variety Ranjit with higher photosynthate partitioning for panicles and has lower CH_4 flux compared to cultivar Agni, with more partitioning towards vegetative growth. Moreover, the extensive root growth intensifies the methane transport to the above-ground parts. Similarly, Das et al., 2008, reported the cultivar Luit with higher photosynthesis rate at reproductive stage showed lower CH_4 emission compared to cultivar Disang having high photosynthetic rate at vegetative stage. Indirect association is observed between capacity of cultivar to fix, translocate, partition and store carbon through photosynthesis with methane emission (Sass and Cicerone, 2009). Gogoi et al., 2008 demonstrated difference in CH_4 emission in Ranjit and Mahsuri cultivars due to their variation in shoot and root biomass. It was inferred that variation in emission peaks were mainly contributed by difference in number and morphology of leaves, tillers and roots which are, again, influenced by genotypic and environmental factors.

Among the varieties, it was found that Koshihikari is a potential cultivar for mitigating CH_4 emission with stable grain yield (Lou et al., 2008). Comparison between two varieties Pusa44 and PR118 presented that Pusa44 had better vegetative growth with significantly higher CH_4 emission (Khosa et al., 2010). Some Indian varieties like Gitesh and Kushal have been found to emit less methane and nitrous oxide (Baruah et al., 2010). Yu et al., 2016, compared super rice variety, Ningjing1 and traditional variety Zhendao11 and reported that total CH_4 emission from Ningjing1 was 35.2% lower and it was mainly contributed by its stronger root system compared to Zhendao11. Based on these facts, high yielding cultivars with less methane emissions may be considered climate resilient for cultivation. However, some studies reported that differences in CH_4 emissions from cultivar are not consistent over time but exhibited high phenotypic flexibility due to environment interactions (Wassmann et al., 2002; Lu et al., 2000; Sun et al., 2016).

Further studies using high throughput phenotyping of rice varieties for morphological as well as physiological traits contributing to methane emission, would immensely favour breeding targets in this direction. Screening genotypes, for gaseous exchange in controlled environment or rhizotrons and multi environment testing, would provide information on genotypes having potential for low methane emission, and also the differences in methane emission in different crop growth stages. The phenotyping platforms designs can be programmed to measure traits like gas transport potential, metabolic activity and root exudates. Moreover, Gutierrez et al., (2013) demonstrated that the digital imaging is more efficient than traditional method in measuring the root oxidation potential.

Association of plant traits to CH_4 emission

Simultaneous accomplishment of methane reduction as well as sustainable rice production must be the focus of any mitigation technology adaptation. The global warming potential can, thus be brought in win-win situation by concentrated efforts on varietal selection and management practices in rice (Minamikawa et al., 2012). Several studies reported that significant correlations were observed between the morphological and anatomical adaptations of genotypes to emissions inspite of the system of cultivation (Table 1). Priority may be given for identification of associated traits and donor genotypes

Table 1: Associated traits contributing to genotypic variation in terms of methane emission

S. No.	Associated traits contribute genotypic variation in terms of methane emission	References
1.	Plant biomass, profuse vegetative growth	Parashar et al., 1997
2.	Plant architecture, metabolic activity and gas transport potential	Sigren et al. 1997; Huang et al., 1998
3.	Gas transport capacity	Butterbach-Bahl et al., 1997 Aulakh et al., 2000 Majumdar, 2003
4.	Plant growth, root length, root volume, root porosity, number of tillers, root mass rooting pattern, metabolic activity	Kim et al., 1999
5.	Nodal development	Aulakh, 2000
6.	Gas conductance through aerenchyma	Aulakh et al., 2000; Mei et al., 2009; Li et al., 2013
7.	Photosynthate partitioning	Das and Baruah, 2008; Das et al., 2008; Sass and Cicerone, 2009
8.	Root length, root weight, above ground biomass, number of tillers	Setyanto et al., 2004
9.	Sugars and organic acids of roots and root exudates and biomass yield	Kerdchoechuen, 2005
10.	Leaf number, tiller number, profuse vegetative growth, leaf area index	Gogoi et al., 2008
11.	Number of tillers per area, the root mass, the rooting pattern, and metabolic activity	Udayasoorian and Sebastian, 2008
12.	Root weight, shoot dry weight, number of tillers, leaf area, aerenchyma	El-Sharkawy et al., 2009
13.	Anatomical features of medullary cavity	Nouchi et al., 1990; Wang et al., 1997; Das and Baruah, 2008
14.	Leaf area, leaf number, tiller number and root dry weight, crop photosynthetic rate	Baruah et al., 2010
15.	Leaf number, tiller number, plant biomass	Uprety et al., 2011
16.	Plant biomass at heading	Simmonds et al., 2014
17.	Tiller number, culm biomass, harvest index , root mass, panicle biomass, oxidation potential of rhizosphere, methane transport capacity of rice roots, culm influence emissions	Qin et al., 2015
18.	Leaf area index, tiller number, leaf and root dry weight, rate of leaf transpiration, stomatal conductance, leaf stomatal frequency, size of the xylem vessels	Borah and Baruah, 2015
19.	Spikelet number	Jiang et al., 2016
20.	Root traits	Zhang et al., 2016
21.	Biomass, root porosity	Jiang et al., 2017

and incorporating them in varietal development. Methane production is correlated with photosynthetic activity and photosynthetic carbon allocation of rice plants (Sass et al., 1991). Therefore, an inverse relation between grain yield and methane release was reported as most of the photosynthetically fixed carbon is stored as grain (Denier van der Gon et al., 2002). High yielding cultivars with low photosynthetic carbon allocation to root have, also, found to decrease methane emissions by providing lower substrate for methanogens (Das and Baruah, 2008). Qin et al., (2015), conducted a two-year field experiment and found tiller number and nitrogen assimilation of leaves as decisive parameters for significant differences in yield scaled methane emission rates among rice cultivars. Butterbach-Bahl et al., (1997) and Aulakh et al., (2000) explained that CH_4 transport capacity is a key factor in differentiating CH_4 emissions between two cultivars. Number, morphological differences and developmental duration of aerenchyma has a direct association with gas transport capacity (Majumdar, 2003). Variation in root and shoot traits, altogether contribute to the average daily CH_4 emission (Lou et al., 2008). More studies have to focus on root and shoot anatomy, so that the genes responsible for anatomical changes causing variations in emissions can be pursued.

In the context of methane emission, the rhizosphere plays a major role as elevated root oxidation potential is essential for methane oxidation (Gutierrez et al., 2014). Cultivars with high root oxidation potential can be preferably selected for low methane emissions. Wide range of variation in cultivars was observed for cumulative CH_4 flux and oxidase activity at the root tip, indicating an indirect effect of root oxidation potential on CH_4 flux (Satpathy et al., 1998). Aulakh et al., (2001), demonstrated positive associations between rates of root exudation with CH_4 production. Kerdchoechuen 2005, compared 4 Thai rice varieties and found that methane emission was related to sugars and organic acids in root exudates. Microbial activity in the paddy field was enhanced due to organic carbon provided from root exudates and root litter. Das and Baruah 2008 suggested that cultivars with intensified reallocation of photosynthates to roots provide more substrate to methanogenic bacteria in the root zone.

Methanogenic and methanotrophic microorganisms also play a key role in the CH_4 emissions (Semrau et al., 2010; Bridgham et al., 2013; Costa and Leigh, 2014; Lee et al., 2015; Han et al., 2016). Win et al., 2011 and Fazli et al., 2013 reported the specificity of rice cultivar on rate of methane oxidation activity and methanotrophic bacteria populations in rhizosphere. Xuan et al., 2011, detected effect of plant type on community structure of methanotrophs. Soil microbial community is also affected by differences in the root exudates, root porosity and oxygenation at rhizosphere which are cultivar depend (Landi et al., 2006; Doornbos et al., 2012). On the contrary, Wu etal. 2009 suggested no significant effect of genotypes on the methanotrophic community. Schutz et al., (1989) reported that, although there is change in methane emissions during growth stages, the concentration of methanogens remained stable.

Breeding rice varieties for reduced methane emission

Climate-adaptive breeding and replacement of obsolete cultivars with climate resilient varieties are key mechanisms to mitigate the impact of climate change (Altin et al., 2017). Identifying genotypic variation through field screening for CH_4 emissions, high temperature, ozone tolerance and nitrogen use efficiency, is required for initiating a successful breeding programme to develop rice cultivars capable of higher yields for climate resilience (Serrano-Silva et al., 2014). The variation available for the CH_4 emission contributing traits among germplasm, opens the opportunity for breeding low methane emitting cultivars. High root oxidizing potential and high harvest index, with less number of unproductive tillers, are the breeding targets to develop an ideal rice cultivar with low CH_4 emission (Wang et al., 1999). Varieties with reduced respiration losses will provide twin benefits of food security and GHG mitigations (Chauhan and Mahajan, 2013). Jiang et al., (2017) reported that breeding high-yielding rice cultivars with higher biomass and increased root porosity is a key strategy to reduce emissions while sustaining rice production by screening 33 rice cultivars. Development of new cultivars with minimum number of unproductive tillers and reduced root permeability can decrease methane emission and it will be promising and are economical way to mitigate methane emissions. A schematic outline of feasible crop improvement steps, to develop improved genotypes with lower methane emission, is given in the Fig. 1.

Breeding can be targeted to achieve reduced CH_4 emissions by designing genotypes with increased rhizosphere and reduced carbon release from root zone. The physiological parameters affecting the methane emissions should be considered for screening while developing varieties. Moreover, the new plant type (NPT) rice cultivars bred for effective number of tillers with few aerenchyma are considered effective for reduced root exudates. It has been shown that the cultivars showing ozone resistance, nitrogen use efficiency and water use efficiency emit less methane. So, the genotypes which have been phenotyped for these related parameters can be used as donors in breeding programmes (Avnery et al., 2013).

In addition, mitigation of methane emissions could be achieved through improved land use applications, better management practices of rice fields, reduced land disturbances, direct sowing and water management practices. Submergence of rice fields can be prevented and shifted to alternative systems of cultivation. So, breeding for these management practices also leads to developing suitable cultivars. The aerobic rice emits 80-85 % lesser methane gas into the atmosphere coupled with higher carbon credits (Parthasarathi et al., 2012; Sandhu et al., 2013, Sritharan et al., 2015). IPCC, 2006 - National Greenhouse Gas Inventories guidelines, assessed an average of 48% reduction in methane emission vis-a-vis normal puddled transplanted field. The aerobic, dry direct seeded rice and alternate wetting and drying (AWD) systems of cultivation are, thus, gaining importance in today's scenario of climate change (Tiago et al., 2016; Sharma et al., 2016; Xu et al., 2015). AWD system along with water conservation, was reported to reduce methane emission in rice by 43% compared to flooded irrigated rice systems (Sanders et al., 2015). On the other hand such adaption to aerobic, rainfed and AWD systems needs genotypes suitable and highly productive in such systems. Breeding of tolerant varieties for water limited conditions will also help in growing rice in unflooded condition, contributing to mitigate the methane emissions.

Studies showed that drought tolerant lines with minimal yield loss under varying water regimes, are more climate resilient in terms of low methane emission and lower water requirement (Zhou and Song, 2014). Shin and Yun, (2000), screened cultivars of different duration and reported that irrespective of growth duration, similar trends were observed in mean daily CH_4 emission as well as integrated seasonal CH_4 flux. However early maturing cultivar emits less cumulative CH_4 in comparison to late maturing cultivars (Setyanto et al., 2000). Developing short-duration varieties with high water use efficiency and per day productivity, also will contribute for reduced methane emission (Sass et.al. 1993; Wang et.al. 1990; Zhang et.al. 2009; Yadav, 2013). Proper and systematic cropping practices, along

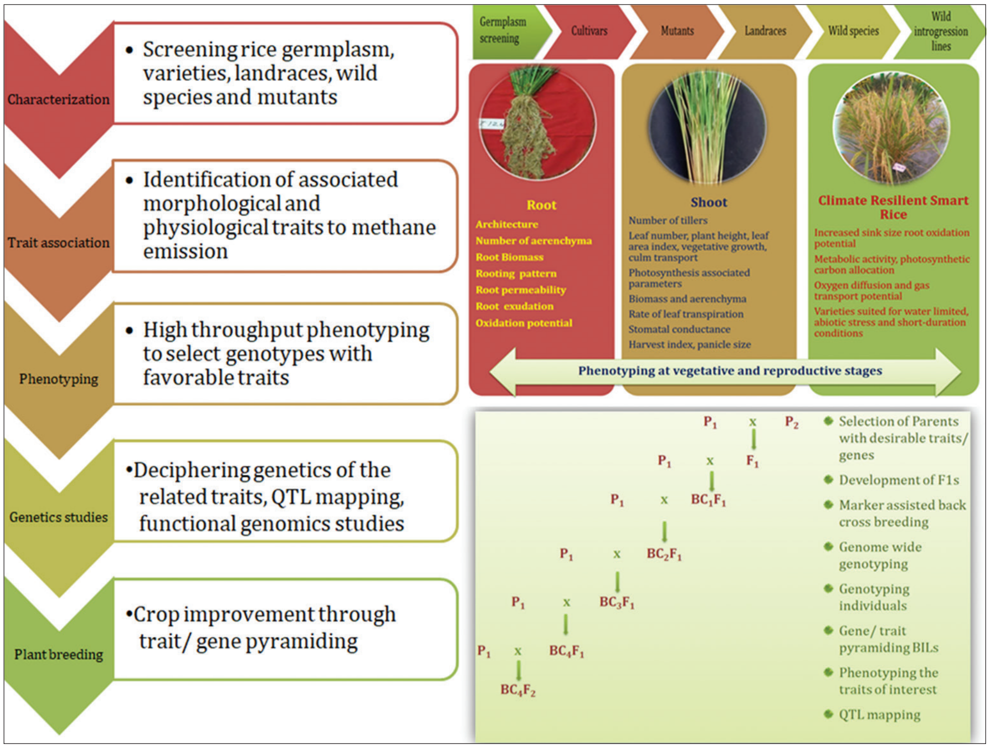

Fig 1. A schematic outline of crop improvement steps for development identification of lines with lower methane emission

with nutrient management especially nitrogen, water and soil management, have also been proved to reduce methane emissions (Xiaohong et al., 2011).

Breeding for climate resilience coupled with low input technologies is the need of the hour for feeding the proliferating world population (Flavell, 2017). Identification of quantitative trait loci (QTL) and candidate genes, related to methane emission and the plant traits which contribute for mitigation, may be explored if large scale phenotyping facilities are available. Association mapping is also an approach for identifying genomic segments underlying the particular region associated with low methane emissions or the related traits in the available germplasm resources. Even the genomic information is sparse on regions associated with low methane emissions, genetic differences and allelic differences can be explored between high and low methane emission rice lines. In addition, molecular tools and new breeding techniques like genome editing will greatly enhance the breeding process and to be integrated for the successful varietal development (Lusser et al., 2011; Flavell, 2017). Genetic engineering is another alternative strategy if there is commercialization and public acceptance to genetically modified crops. Su et al., (2015), engineered rice for less methane emission by expressing the barley transcription factor SUBIBA2 (HvSUSIBA2) in rice cultivar, Nipponbare. Three years of trials in China showed reduction in methane emissions from the fields and reduced rhizospheric methanogen levels. Such methods can be further elevated to a large scale and commercialized.

Endophytic microorganisms *viz.* methanotrophs have been found promising in mitigating methane production in crops other than rice (Stepniewska and Kuzniar, 2013). Under aerobic soils, the methanotrophs can metabolize methane through biological oxidation to the tune of 90% (Chowdhury and Dick, 2013). In case of inundated paddy fields, methane-oxidizing bacteria are present in the water-soil interface (Cicerone and Oremland1988). Oxidation of methane has been reported to limit diffusion of methane up to 60% to the atmosphere (Sass et al., 1991). The supply of atmospheric oxygen to the roots by rice plants through aerenchyma along with methane-oxidizing bacteria, results in reduced methane emission (Nouchi et al., 1991; Serrano-Silva et al., 2014). Such rice associated methanotrophs can be utilized for methane mitigation in rice. Genomics technologies revealed role of different microbes in determining crop traits that can be further improved for target traits (Flavell, 2017; Alpana et al., 2017). Metagenomics, tools can be employed very well for studying the diversity of methanotrophs in the rice rhizosphere and will have direct impact of genotypic traits in their population, structure and their oxidation capacity. Zhang et al., (2016) reported that diurnal variations of CH_4 emissions are influenced by Arbuscular Mycorrhizal Fungi (AMF).

The digital image based on geospatial analysis platforms are, now, readily available and can be deployed for estimation of methane emission in specific areas. Based on the simulation studies it was observed that early duration rice cultivars with short growing seasons emit less methane (Serrano-Silva et al., 2014). Hasan et al., (2013), reported that short duration varieties are the best mitigation strategy based on multi criteria evaluation with weighted summation method. Moreover, crop simulation modelling along with meta analysis can also aid in designing models for reduced methane emissions from rice fields (Matthews et al., 2000; Ananda et al., 2004; Babu et al., 2005; Zhang et al., 2011) and action-oriented research towards crop-climate models are essential (Campbell et al. 2016) and the information obtained can be integrated in crop improvement.

Improved varieties from plant breeding and their adaptation in agriculture, sustained the global food security since green revolution. There is a need to identify the plant contributing traits which affect the methane emission through large scale genetic studies and multi environment testing. It will facilitate the identification and breeding of suitable cultivars for eco-friendly, low methane emitting high yielding rice varieties with more accuracy. Appropriate choice of rice cultivars with associated traits for low methane emission and utilization in crop improvement is very essential.

CONCLUSION

Methane emission is anticipated to upsurge while meeting the challenges of global food security with existing cultivars and traditional agronomical practices for rice production. Morphological, anatomical, microbiological and physiological parameters of rice need to be studied in detail to understand the mechanisms involved in methane emission. The combined strategy can be well employed in breeding programmes reflecting, all together, a new avenue for climate smart rice. More studies are needed to understand the inheritance of underlying traits and their yield potential. Cultivation of high-yielding rice cultivars, with a low gas transport capacity, represents an economic and promising approach to reduce methane emissions. Utilization of feasible mitigation technologies and suitable cultivars helps in sustainable yield improvement without radical changes in cultural practices and food habits.

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