SUMMARY
There is worldwide concern over the increasing atmospheric concentration of ‘greenhouse gases’ such as CO$_2$, CH$_4$ and N$_2$O that are implicated in ‘global warming’. The contribution of CH$_4$ amounts to 15% of the enhanced global warming. Predominantly anaerobic soils of flooded rice fields constitute an important source of atmospheric CH$_4$. Anthropogenic emission of CH$_4$ largely stems from agricultural activities including rice cultivation. Intensive rice cultivation to meet the food requirements of the ever increasing human population would certainly increase CH$_4$ emission. But, there are uncertainties and gaps in our knowledge on the exact contribution of rice fields to global CH$_4$ budget and the factors governing CH$_4$ emission. Experiments were, therefore, conducted in the present study to determine:

- CH$_4$ emission from upland crops preceding a low land rice crop and from a rice-rice cropping system;
- role of water regime on CH$_4$ efflux from an alluvial soil planted to rice under greenhouse conditions;
- CH$_4$ emission from rice fields under the influence of split application of urea-N;
- CH$_4$ production in flooded soils amended with different forms of inorganic-N fertilizers;
- cultivar variation in CH$_4$ emission from flooded rice fields;
- impact of salinity on CH$_4$ production in flooded alluvial soil; and
- CH$_4$ production in flooded soils amended with heavy metals.

For estimation of CH$_4$ emission in greenhouse and field studies, the manual closed chamber method was employed. Air samples from the closed chamber were collected in Tedlar® gas sampling bags for 30 min each in the morning and in the afternoon at periodic intervals and then analyzed for CH$_4$ by gas chromatography. In laboratory incubation studies, CH$_4$ production in soil samples contained in vacutainer tubes was estimated by injecting the head space gas samples to a gas chromatograph fitted with flame ionization detector.
In a field study, CH$_4$ emission from soils planted to upland crops preceding a lowland rice crop and from a rice-rice cropping system was investigated. CH$_4$ emission was very low (less than 3 mg m$^{-2}$ d$^{-1}$) in all the field plots planted to upland crops (mustard, chickpea and blackgram). Cumulative CH$_4$ flux from the lowland rice crop was substantial but CH$_4$ emission from the rice-rice rotation was considerably higher than the upland crop-rice rotation. The present study clearly demonstrates that growing a dryland crop in rotation with flooded rice can substantially reduce CH$_4$ flux.

In a greenhouse experiment, the effect of moisture regime (continuously flooded, continuously nonflooded, intermittently flooded) on CH$_4$ efflux from an alluvial soil planted to rice was studied. During a crop season, CH$_4$ efflux was almost 10 times more pronounced under continuously flooded conditions than under continuously nonflooded conditions. Intermittently flooded regime (alternate flooded and nonflooded cycles of 40 or 20 days each) emitted distinctly less CH$_4$ than the continuously flooded system. A significant correlation existed between CH$_4$ emission under different water regimes and rhizosphere redox potential and extractable Fe$^{2+}$ content. The highly significant correlation between readily mineralizable carbon (RMC) content and CH$_4$ indicate that RMC is one of the important factor influencing CH$_4$ emission from flooded rice soils. Root biomass also exhibited a positive correlation with CH$_4$ emission. Results indicate that well-timed short drainage periods, during the growing seasons can reduce CH$_4$ emissions without adversely affecting the grain yield. This study also indicates that in a rainfed rice ecosystem where rainy periods are usually interspersed by short spells of drought, CH$_4$ emission can be lower than that from irrigated or continuously flooded situations.

In a field study, the effect of split application of urea-N on CH$_4$ efflux from flooded rice fields was investigated. Cumulative CH$_4$ efflux followed the order of no N < 90 kg urea-N ha$^{-1}$ (30-30-30) < 90 kg urea -N ha$^{-1}$ (45-22.5-22.5) < 120 kg urea-N ha$^{-1}$ (60-30-30) < 120 kg urea-N ha$^{-1}$ (40-40-40). Split application of urea-N at various levels and stages of plant growth also influenced the onset of peak CH$_4$ efflux. Higher percentage (62.5%) of total CH$_4$ efflux was emitted in the first half of the growing period at high nitrogen levels. Extractable Fe$^{2+}$ and ninhydrin reactive nitrogen (NRN) content of the soil exhibited a significant relationship with CH$_4$ emission. An inverse relationship was
observed between dissolved oxygen and CH$_4$ emission. Interestingly, Fe$^{2+}$ content, an indicator of reduction status of a soil, showed a significant negative relationship. Total dry matter accumulation (TDMA) was lowest in no N control and highest in 120 kg urea-N ha$^{-1}$ applied at a split of 60-30-30. However, none of the plant parameters studied in this experiment showed any significant relationship with CH$_4$ emission. The present study indicates that split application of fertilizer-N, recommended to derive better utilisation of the applied fertilizer, may reduce CH$_4$ efflux from rice paddy, both in terms of appearance of emission maxima as well as cumulative CH$_4$ efflux.

In a laboratory incubation study, the effect of different forms of inorganic N fertilizer applied at low (20 µg N g$^{-1}$ soil) and high (40 µg N g$^{-1}$ soil) levels on CH$_4$ production was studied under flooded conditions. In soil amended with N-fertilizer at 20 µg N g$^{-1}$ soil, application of (NH$_4$)$_2$SO$_4$ inhibited CH$_4$ production, while urea was stimulatory. Application of other forms of nitrogen (NH$_4$Cl, NH$_4$NO$_3$, KNO$_3$) did not result in any significant difference in CH$_4$ production over that of no-N control. Interestingly, in soil amended with 40 µg N g$^{-1}$ soil, almost all forms of N-fertilizers, inhibited CH$_4$ production. Mean CH$_4$ production was inhibited by 28, 17, 17, 27 and 25% in KNO$_3$, NH$_4$Cl, NH$_4$NO$_3$, (NH$_4$)$_2$SO$_4$ and urea amended soil respectively over that of no-N control. While inhibitory effect of KNO$_3$ was more prominent at initial stages, inhibition of CH$_4$ production in (NH$_4$)$_2$SO$_4$ amended soil, on the other hand, was more pronounced between 30-45 d and continued even thereafter. Reduction in CH$_4$ production by nitrate and sulphate may be due to their ability to maintain the flooded soil under oxidised conditions. Besides, sulphate reducing bacteria may outcompete methanogenic bacteria for substrates in sulphate-rich environments and thus reduce CH$_4$ emission. Readily mineralizable carbon (RMC) content was distinctly less in fertilizer amended soils, irrespective of the type of fertilizer, than that in unamended soil. Application of fertilizer N, especially at higher levels, resulted in better utilization of available carbon causing a restriction in the supply of methanogenic substrates and consequently reduced CH$_4$ emission. A significant linear relationship existed between RMC content and CH$_4$ production in fertilizer-amended soils at both low and high N levels. Correlation analysis showed highly significant relationship between ninhydrin reactive nitrogen (NRN) content and CH$_4$ production at both low and high level of fertilizer N levels.
In a field study with eleven rice cultivars, rice variety showed a significant ($P < 0.05$) effect on $\text{CH}_4$ efflux. Based on cumulative $\text{CH}_4$ efflux values, rice varieties used in this study could be grouped into: (i) low $\text{CH}_4$ emitters ($< 10 \text{ g m}^{-2}$) (ii) medium $\text{CH}_4$ emitters ($10-20 \text{ g m}^{-2}$) and (iii) high $\text{CH}_4$ emitters ($> 20 \text{ g m}^{-2}$). $\text{CH}_4$ efflux among the different rice cultivars was also growth stage dependent. $\text{CH}_4$ emission peaked at vegetative stage in cv Dhalaheera, Sneha and Vanaprabha and around reproductive stage in cv Vandana. Rhizosphere characteristics of different rice cultivars including redox potential and RMC content had significant relationship with $\text{CH}_4$ emission. Likewise above and underground biomass had significant relationship with $\text{CH}_4$ emission.

In a laboratory incubation study, effect of salts of different anions on $\text{CH}_4$ production was studied. Amendment of the nonsaline alluvial soil with salt to bring pore water EC to 8.0 resulted in a strong inhibition of $\text{CH}_4$ production. The inhibitory effect of anions imparting salinity, followed the order of $\text{SO}_4^{2-} > \text{Cl}^- > \text{HCO}_3^-$. Sulphate stimulated population of sulphate reducing bacteria which in turn outcompete methanogens for substrates and thereby inhibited methanogenesis. Chloride, on the other hand, causes osmotic imbalance by adversely affecting the cation-anion equilibrium and thereby inhibited methanogens and/or microorganisms that produce substrates for methanogens. So was the case of amendment with $\text{HCO}_3^-$. Salinity mediated by different anions adversely affected methanogenic activity by limiting the substrate concentration (RMC) for methanogens as well as methanogenic population. These results also suggest that $\text{CH}_4$ emission can be less pronounced in coastal saline soil than that in non-coastal saline soil.

In another laboratory incubation experiment, effect of select heavy metals on $\text{CH}_4$ production in three soils was studied. Heavy metals behaved differently in their effect on methanogenesis and $\text{CH}_4$ producing bacteria. Heavy metals such as Cd, Cu and Pb inhibited $\text{CH}_4$ production in all the soils. Zn stimulated $\text{CH}_4$ production in alluvial soil, but inhibited it in laterite and acid sulphate soils. Cr, effectively inhibited $\text{CH}_4$ production in alluvial soil, but stimulated it in laterite and acid sulphate soils. Population of aerobic microorganisms was little affected by the heavy metals used while anaerobic bacterial population was inhibited by heavy metals. The stimulatory effect of Zn and the inhibitory
The effect of Cr on methanogenesis in alluvial soil was attributed to their stimulation or inhibition of methanogenic bacterial population.

To sum up, the present study demonstrates:

- low emission of CH\(_4\) from an upland crop-rice rotation than from a rice-rice rotation suggesting crop diversification as one of the feasible options to reduce CH\(_4\) emission;
- distinctly less pronounced CH\(_4\) emission from intermittently flooded regime than that from continuously flooded regime, without a drastic reduction in grain yield;
- significant positive correlation between RMC content and CH\(_4\) emission in soil samples under different water regimes;
- possible mitigation of CH\(_4\) emission from rice fields by judicious N management through split application and use of appropriate form of N-fertilizer;
- significant variation in CH\(_4\) emission from flooded fields planted to different rice cultivars, attributed to plant and rhizosphere parameters;
- inhibition of CH\(_4\) production by different anions in flooded soils by limiting the substrate concentration (RMC) for methanogens as well as methanogenic population in a flooded soil; and
- inhibition of CH\(_4\) production by heavy metals, Cd, Cu and Pb and the population of methanogens.