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Biogeochemical Aspect of Atmospheric Methane and Impact of Nanoparticles on Methanotrophs

Parul Rajput[1]*, Rupali Saxena[1], Gourav Mishra[1], SR Mohanty[2] and Archana Tiwari[1]

[1]*School of Biotechnology, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal, Madhya Pradesh, India*
[2]*Soil Biology, Indian Institute of Soil Sciences (ICAR), Nabibagh, Bhopal, Madhya Pradesh, India*

Abstract

Increasing concentration of atmospheric greenhouse gas and its implications to the global climate change is a major concern. Methane (CH_4) emitted from terrestrial ecosystem by human activities and or by natural processes gets oxidized by certain group of soil microbes. Any imbalance or negative impact on these microbial groups may lead to ecosystem collapse. Due to rapid industrialization there is increasing threat of various environmental pollutants on the soil microbes. One of the recently identified pollutants is nanoparticles. This paper reviews the impact of nanoparticles on the global climate regulating methanotrophs and potential negative or positive impact of nanoparticles on the soil microbes. Here we assessed the effects of metal nanoparticles on the microorganisms and also the physiology and phylogeny of methanotrophs. Altogether, the study suggests that metal nanoparticle could significantly produce ecotoxicity and killing of phytostimulatory soil bacteria. Thus, the engineered nanoparticle (ENPs) should be further tested as a possible ecofriendly agent.

Keywords: Methanotrophs; Nanoparticles; Methane; Oxidation

Introduction

Microbial mediated methane (CH_4) oxidation play a major role in reducing global atmospheric CH4 and annually about 10-40 Tg atmospheric CH_4 is consumed by methane oxidizing microbes [1-4]. Microbial CH_4 oxidation has been reported to occur at significant rates in many natural ecosystems and soils can act as sinks for CH_4 from atmosphere [5-10]. Therefore the biological CH4 oxidation process is important process to minimize global climate change and there is need of extensive research to characterize methanotrophic activity in various ecosystems for possible application to reduce atmospheric greenhouse gas. CH_4 is produced anaerobically from flooded rice field while its oxidation takes place under aerobic condition. So far most of the studies characterizing methane oxidation rate are restricted to upland aerobic soil ecosystem and limited information are there to support our understanding in flooded soil ecosystem [7,11-13]. Soil moisture is important to regulate soil CH4 oxidation [14] either by affecting diffusion of gas phase [15] or affect soil methanotrophs metabolism by osmotic stress [16] In increased moisture containing wetter soils, CH_4 oxidation decreases with higher soil moisture [17-20], but at lower soil moistures CH_4 oxidation is not highly correlated with soil moisture [21-23]. Typically in very dry soils such as in deserts, CH_4 oxidation is higher after precipitation [24]. In such soils osmotic stress may limit activity of CH_4-oxidizing bacteria more than diffusion of gases through the soil [16]. Few studies have revealed that water addition to soil can stimulate CH_4 oxidation and methanotrophic activity maxima can be attained at intermediate soil moistures [25,26]. It has been projected that climate change will affect the water distribution globally and increasing temperature will lead to more wet lands [27,28]. Many upland soils will remain flooded and this may influence the green house gas (GHG) foot print by affecting both methanogenic and methanotrophic bacteria.

In a flooded rice soil, CH_4 oxidation activity varies with cropping period [29]. Under flooded condition anaerobic microbes are predominantly active and reduces aerobic microbial metabolism. However flooded soil does not necessarily result in the development of uniformly reduced profile. A thin, oxidized surface horizon overlying a deep, reduced horizon is formed due to the dissolved oxygen from the overlying floodwater diffusing across the surface water-soil interface and in soils planted with rice, the rhizosphere is oxidized because of the delivery of oxygen (O_2) into roots [30-32]. In periodically submerged soil, anaerobic microbial redox metabolism takes place by sequential reduction of inorganic electron acceptors such as oxygen, nitrate, manganese (IV), iron (III), sulphate and carbon dioxide (CO_2). The sequence of reduction processes is best described by the thermodynamic theory, which predicts preferential reduction of available electron acceptors with the most positive redox potential [33,34] Many studies have investigated on the impact of oxidized electron acceptors on methanogenic microbes in flooded rice field soil [35,36]. In anaerobic layer anaerobic microbes like denitrifiers, dissimilatory iron reducers, sulphate reducers, and methanogenic bacteria are active in presence of high input of labile organic material. These microbial groups are often competing for common reduced carbon sources [37-39]. In the flooded soil ecosystem CH_4 oxidation activity is affected due to O_2 limitation and along with predominance of reduced species [40,41]. Under such anaerobic condition i.e absence of O_2, CH_4 oxidation has been reported at the less reduced site through NO^{3}-, Fe^{3}+and SO_4^{2}- reduction [42,43] Anaerobic CH_4 oxidation is poorly understood process because the microorganisms capable of performing this process have not been characterized from soil. The significance of increasing concentration of greenhouse gas, CH_4 in the atmosphere and its role in the global warming has been reviewed earlier [44-47]. Flooded soil ecosystems are considered as one of the major sources of CH_4 to the atmosphere and this process is governed by many factors like moisture regime, temperature, organic matter (added or native), sulphate, pH,

***Corresponding author:** Parul Rajput, School of Biotechnology, Rajiv Gandhi Proudyogiki Vishwavidyalaya, Airport Bypass Road, Bhopal-462033, Madhya Pradesh, India, E-mail: rparul21@gmail.com

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aquatic plant related factors [48,49]. CH_4 oxidation acts as sink to the atmospheric CH_4. This activity is carried out by specific microbial groups known as methanotrophs. The following literature review is concerned with the significance of CH_4 as the greenhouse gas, its role in global warming, the sources, and sinks of CH_4 i.e. CH_4 oxidation and factors affecting the processes.

Nanoparticles released from products and applications can get directly or indirectly to the soil. Direct soil contamination occurs from purposefully applying products like biocides, compost, fertilizer, and nanoparticles for remediation, and products which contaminate soil unintentionally like abraded material, some coating materials, contaminated soils, and water for irrigation. Product ingredients reaching soils indirectly on the other hand are released to other environmental compartments e.g. air, water, or groundwater. Thus nanoparticles get exchanged between the environmental compartments.

Methanotrophs physiology

Methanotroph bacterias consume methane for energy and carbon [50]. All known methanotrophs under α-and γ-proteobacteria phyla oxidize methane ultimately to carbon dioxide. Basically 3 types of pathways are followed by methanotrophs. In the general methanotrophic pathway, methane is initially hydroxylated to methanol by pMMO(particulate methane monooxygenase) or sMMO (soluble methane monooxygenase), which is further oxidized to formaldehyde by periplasmic methanol dehydrogenase (MDH) [51]. In the catabolic pathway, formaldehyde is oxidized to CO_2 via formate by formaldehyde dehydrogenase (FalDH) and formate dehydrogenase (FDH), yielding reducing equivalents as either quinol or NADH. In the anabolic pathway, formaldehyde is incorporated into cell biomass via incorporation into either ribulose monophosphate (RuMP) or serine pathway, depending on the type of methanotroph.

Phylogeny

Methanotrophic bacteria are classified into one of two major groups, type I and type II. The major distinction between the two types is the pathway via which formaldehyde is incorporated into cell biomass. Type I methanotrophs assimilate biomass via ribulose monophosphate (RuMP) pathway, while type II methanotrophs use serine pathway for the same operation. Also, there are other notable differences that are used to distinguish these groups of methanotrophs other than biomass assimilation pathway such as cell morphology, composition of phospholipid fatty acids, and membrane arrangements as listed in Table 1.

Atmospheric Methane and Global Warming

In stratosphere, CH_4 influences ozone (O_3) by secluding O_3 by destroying Cl-atoms into HCl molecules which on reaction with–OH radicals releases O_3 depleting Cl-and ClO-radicals. It also undergoes photochemical oxidation and produces water vapour that reacts with O_3 destroying NO and NO_2 to less reactive HNO_3 [52,53]. CH_4 contributes about 15-20% of the current increase in global warming [49]. In addition to general climatologically effects, global warming may affect the global carbon cycle by greatly reducing the soil organic carbon content, which may be released as CO_2 and is likely to add to the current burden of CO_2 in the atmosphere [54].

Characteristic	Type 1	Type 2
Cell morphology	Short rods, usually occur singly; some cocci or ellipsoids	Crescent-shaped rods, rods, pear-shaped cells, sometimes occur in rosettes
G+C content of DNA (mol%)	49-60	62-67
Nitrogen fixation	No	Yes
RuMP pathway present	Yes	No
Serine pathway	No	Yes

Table 1: Differential biochemical and physiological characteristics of type I and II methanotrophic bacteria [51].

Sources and Sinks of Atmospheric Methane

CH4 production can be from biological and abiological sources. The abiological sources such as mining, transport, fossoil fuels, and biomass burning contribute about 20-30% to the total atmospheric CH_4 (Figure 1). The main sink of atmospheric CH_4 is its reaction with–OH radicals [55]. The build up in the global atmospheric CH_4 concentration is attributed to many activities including the bacteria mediated methanogenesis (microbial CH_4) occurring in the anoxic ecosystems and the thermocatalytic reactions (thermogenic CH_4) during petroleum formation [56].

Biogeochemical Cycling of Methane

The primary producer i.e plants fix carbon atoms photosynthetically into a myriad of organic molecules, varying in size and complexity, but all being intermediate in redox potential between CO_2 and CH_4. In anoxic (anaerobic) conditions, organic materials are converted into organic acids, alcohols, methylated amines and H_2 by microbial communities [57,58]. Under highly reducing conditions and in the absence of other potential electron acceptors such as NO^{3-}, SO_4^{2-}, or Fe^{3+}, these substrates can be converted to CH_4 by strict anaerobic methanogenic bacteria [59]. CH_4 thus formed enters the atmosphere at or near earth's surface after escape from methanogenic habitats including wetland, rice paddies and other sources. A high redox potential equals to well-aerated environmental conditions and a low redox potential equals to saturated environmental conditions. Saturated soils become depleted of oxygen, because this is rapidly consumed by aerobic organisms and cannot be replenished by diffusion quickly. Then, anaerobic and facultative organisms continue the decomposition process. In the absence of oxygen, other electron acceptors begin to function, depending on their tendency to accept electrons. When flooding occurs the reduction of the remaining oxygen will take place first, followed by the reduction of nitrate, then manganese, iron, sulphate, and carbon dioxide. The reduction of oxygen occurs by the O_2 consumption of aerobic organisms, NO_3 serves as a biochemical electron acceptor involving N-organisms that ultimately excrete reduced N, the reduction of Mn can be initiated

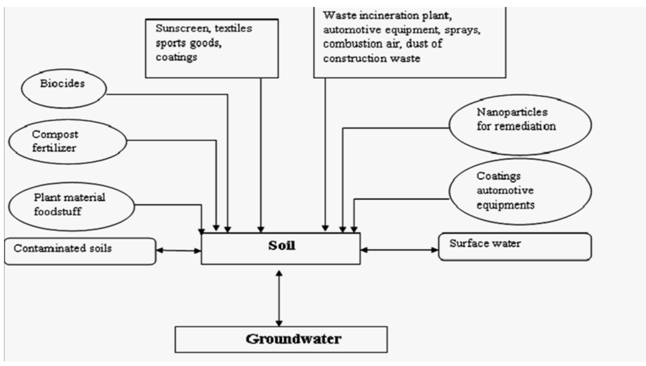

Figure 1: Route of environmental nanoparticles.

in presence of NO^{3-}, whereas the reduction of Fe cannot be initiated in presence of NO^{3-}, and sulphate reducing bacteria are involved to reduce SO_4^{2-}. The sequential reduction of the different electron acceptors in soil is assumed to be due to different types of microorganisms that compete for common electron donors with greater efficiency according to the redox potential of the electron acceptors [60]. For example, the two most important immediate precursors for CH_4 formation are acetate and H_2 for which, however, SO_{4-} -reducing and Fe^{3+}-reducing bacteria compete successfully, if SO_{4-} and Fe^{3+} are available, respectively. CH_4 production in anoxic rice paddies begins only if all the other redox processes, i.e. reduction of NO_3, Fe^{3+} and SO_4- are finished. Methanogenesis is inhibited by competition for H_2, if SO_{4-} reduction and Fe^{3+} reduction was made possible by addition of SO_{4-} and Fe^{3+}, respectively. About 85% of the total CH_4 input flux is consumed by tropospheric OH, producing CO_2, H_2O, CO, H_2 and various intermediate products. The remaining flux enters the stratosphere. Reaction with stratospheric OH is the dominant sink, followed by reaction with O and Cl atoms. Under anoxic conditions CH_4 is oxidized in the presence of electron acceptors with sugar as the end product [42]. Sugar thus formed is oxidized by other microorganisms with ultimate CO_2 formation. In the presence of oxygen, CH_4 is oxidized to CO_2 by methanotrophic bacteria. The oxidation of CH_4 to CO_2 completes the carbon cycle.

Oxidation of Methane by Methanotrophs

The capability of methanotrophs to degrade a wide variety of potential pollutants, including methane and halogenated hydrocarbons, has been studied for applications in climate change control and bioremediation [61-71]. Methane is an important greenhouse gas contributing to global climate change. Although present in relatively small concentrations in the atmosphere, ~1.7 ppmv, methane is approximately 25 times as efficient as carbon dioxide at absorbing infrared radiation [72,73] and the atmospheric methane concentration has risen rapidly since the industrial revolution. The increase in atmospheric methane concentration is attributed to increased anthropogenic methane emissions, which have led to a disruption of global methane cycling [72]. A significant portion of natural and anthropogenic methane generation occurs via biological methanogenesis. Strictly anaerobic environments such as wetlands and landfills promote microbial methanogenesis and thus, are major sources of the atmospheric methane. It is known, however, that significant amounts of methane are also emitted from upland forest soils, ruminant animals, and fossil fuel combustion [74].

Degradation of atmospheric methane occurs via two general pathways: (1) photochemical elimination and (2) microbial oxidation [75]. In photochemical elimination processes, atmospheric methane is primarily degraded through reactions in the stratosphere with either the hydroxyl radical (OH•) or electronically excited singlet oxygen (O1D) [76]. It is estimated that methanotrophic consumption of methane accounts for 1-15% of the combined amount of biotic and abiotic methane removal [77]. In natural environments, e.g., wetlands, methanotrophs are known to oxidize a significant portion of methane generated in anaerobic zones with reported methane oxidation potentials of up to 0.29 μmol CH_4/g wet peat-h [78]. It is also known that methanotrophs in landfill cover soils significantly reduce the amount of methane released from landfills. Methane oxidation potentials up to 10.8 μmol CH_t/g dry weight of soil-h were reported in in vitro experiments performed with landfill cover soils [79].

Nanoparticles Flow between Soil and Its Environment

Nanoparticles come to the soil and leave it through various processes. Out of information on nanoparticles applications found in web and literature studies, a chart of nanoparticles fluxes to and from soil could be drawn (see Figure 1). Included are only fluxes within the system boundary.

Of major relevance for soil contamination are the directly applied products and nanoparticle applications with indirect flows to the soil, either because of mass production or high concentrations of nanoparticles in the products. These are especially automotive equipments, biocides, fertilizers, soil remediation, irrigation, coatings, and air deposition.

Effects of Nanoparticles on Soil Microbes

Several researches revealed that nanoparticles impact terrestrial organisms. Mostly the aquatic organisms are exposed to nanoparticles primarily through gut intake followed by translocation within the body [80,81]. Terrestrial animals are exposed through the lung (inhalation) and gut (diet), while plants are most likely to be exposed via root uptake. Nanoparticles can diffuse through the cell membrane or can be taken up by adhesion and endocytosis. A consistent body of evidence shows that nano-sized particles are taken up by a wide variety of mammalian cell types, are able to cross the cell membrane and become internalized [82-84]. The uptake on NP is size-dependent [85,86]. The uptake occurs via endocytosis or by phagocytosis in specialized cells. They are not dependent upon the circulatory system but can move through the body via cell-to-cell contact. This is a very important consideration in understanding nanoparticle distribution and metabolism within organisms. Potential mechanisms of toxic action within an organism include: disruption of membranes or membrane potential, formation of reactive oxygen species, oxidation of proteins, interruption of energy transduction, release of toxic constituents, and genotoxicity [87]. Antibacterial activity occurs as a direct contact between a positively charged nanoparticle and the bacterial cell surface. This changes the surface phosphorylation and membrane permeability, causes oxidative stress and formation of highly reactive epoxides resulting in DNA damage, and affects the integrity of the bacterial cell membrane.

Conclusion

There is currently a lot of attention being paid to the behaviour and effects of engineered NP, but there is still only limited solid information. However, the mechanisms underlying the nanoecotoxicity potential of ENPs are still not clear enough. Nanotechnology applications in food and agriculture are in its nascent stage. Moreover, some guidance is needed as to which precautionary measures are warranted in order to encourage the development of "green nanotechnologies" and other future innovative technologies, while at the same time minimizing the potential for adverse effects on human health and/or the environment. Thus there is urgent need for a systematic evaluation of the potential adverse effect of nanotechnology. It is therefore recommended that the ecotoxicological effect of nanomaterial be clarified before their application.

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References

1. Hardy KR, King GM (2001) Enrichment of high-affinity CO oxidizers in Maine forest soil. Appl Environ Microbiol 67: 3671-3676.
2. Roslev P, King GM (1995) Aerobic and anaerobic starvation metabolism in methanotrophic bacteria. Appl Environ Microbiol 61: 1563-1570.
3. Reeburgh WS (2003) Global Methane Biogeochemistry. Treatise on Geochemistry 4: 65-89.

4. Reeburg WS, Murrell JC, Kelly JP (1993) The role of methanotrophy in the global methane budget. In Microbial growth on C-1 compounds, Intercept Ltd, United Kingdom.

5. Kightley D, Nedwell DB, Cooper M (1995) Capacity for methane oxidation in landfill cover soils measured in laboratory-scale soil microcosms. Appl Environ Microbiol 61: 592-601.

6. Börjesson G, Chanton J, Svensson BH (2001) Methane oxidation in two Swedish landfill covers measured with carbon-13 to carbon-12 isotope ratios. J Environ Qual 30: 369-376.

7. Conrad R, Rothfuss F (1991) Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. Biol Fert Soils 12: 28-32.

8. Suwanwaree P, Robertson GP (2005) Methane Oxidation in Forest, Successional, and No-till Agricultural Ecosystems. Soil Sci Soc Am J 69: 1722-1729.

9. Boetius A, Ravenschlag K, Schubert CJ, Rickert D, Widdel F, et al. (2000) A marine microbial consortium apparently mediating anaerobic oxidation of methane. Nature 407: 623-626.

10. Hütsch WB, Webster CP, Powlson DS (1994) Methane oxidation in soil as affected by land use, soil pH and N fertilization. Soil Biol Biochem 26: 1613-1622.

11. Bronson KF, Mosier AR (1994) Suppression of methane oxidation in aerobic soil by nitrogen fertilizers, nitrification inhibitors, and urease inhibitors. Biol Fert Soils 17: 263-268.

12. Mohanty SR, Bodelier PL, Floris V, Conrad R (2006) Differential effects of nitrogenous fertilizers on methane-consuming microbes in rice field and forest soils. Appl Environ Microbiol 72: 1346-1354.

13. Grosso SJD, Parton WJ, Mosier AR, Ojima DS, Potter CS, et al. (2000) General CH4 oxidation model and comparisons of CH4 Oxidation in natural and managed systems. Global Biogeochem Cycles 14: 999-1019.

14. Mancinelli RL (1995) The regulation of methane oxidation in soil. Annu Rev Microbiol 49: 581-605.

15. Striegl RG (1993) Diffusional limits to the consumption of atmospheric methane by soils. Chemosphere 26: 715-720.

16. Schnell S, King GM (1996) Responses of methanotrophic activity in soils and cultures to water stress. Appl Environ Microbiol 62: 3203-3209.

17. Steudler PA, Bowden RD, Melillo JM, Aber JD (1989) Influence of nitrogen fertilization on methane uptake in temperate forest soils. Nature 341: 314-316.

18. Whalen SC, Reeburgh WS (1990) Consumption of atmospheric methane by tundra soils. Nature 346: 160-162.

19. Adamsen AP, King GM (1993) Methane consumption in temperate and subarctic forest soils: rates, vertical zonation, and responses to water and nitrogen. Appl Environ Microbiol 59: 485-490.

20. Keller M, Reiners WA (1994) Soil-atmosphere exchange of nitrous oxide, nitric oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa Rica. Global Biogeochem Cycles 8: 399-409.

21. Castro MS, Steudler PA, Melillo JM, Aber JD, Bowden RD (1995) Factors controlling atmospheric methane consumption by temperate forest soils. Global Biogeochem Cycles 9: 1-10.

22. Dunfield PF, Yuryev A, Senin P, Smirnova AV, Stott MB, et al. (2007) Methane oxidation by an extremely acidophilic bacterium of the phylum Verrucomicrobia. Nature 450: 879-882.

23. Mosier AR, Parton WJ, Valentine DW, Ojima DS, Schime DS, et al. (1996) CH4 and N2O fluxes in the Colorado shortgrass steppe: 1. Impact of landscape and nitrogen addition. Global Biogeochem Cycles 10: 387-399.

24. Strieg RG, McConnaughey TA, Thorstenson DC, Weeks EP, Woodward JC (1992) Consumption of atmospheric methane by desert soils. Nature 357: 145-147.

25. Czepiel PM, Crill PM, Harriss RC (1995) Environmental factors influencing the variability of methane oxidation in temperate zone soils. J Geophys Res 100: 9359-9364.

26. Torn M, Harte J (1996) Methane consumption by montane soils: implications for positive and negative feedback with climatic change. Biogeochemistry 32: 53-67.

27. Walther GR, Post E, Convey P, Menzel A, Parmesan C, et al. (2002) Ecological responses to recent climate change. Nature 416: 389-395.

28. Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173.

29. Dannenberg S, Conrad R (1999) Effect of rice plants on methane production and rhizospheric metabolism in paddy soil. Biogeochemistry 45: 53-71.

30. Engler RM, WH Patrick (1974) Nitrate Removal from Floodwater Overlying Flooded Soils and Sediments. J Environ Qual 3: 409-413.

31. Bosse U, Frenzel P (1997) Activity and Distribution of Methane-Oxidizing Bacteria in Flooded Rice Soil Microcosms and in Rice Plants (Oryza sativa). Appl Environ Microbiol 63: 1199-1207.

32. Bodelier PL, Frenzel P (1999) Contribution of methanotrophic and nitrifying bacteria to CH4 and NH4+ oxidation in the rhizosphere of rice plants as determined by new methods of discrimination Appl Environ Microbiol 65: 1826-1833.

33. Ponnamperuma FN (1972) The Chemistry of Submerged Soils. Advances in Agronomy, Brady NC, Academic Press, USA

34. Zehnder AJB, Stumm W (1988) Geochemistry and biogeochemistry of anaerobic habitats. Biology of anaerobic microorganisms, John Wiley & Sons, New York, USA

35. Bond DR, Lovley DR (2002) Reduction of Fe(III) oxide by methanogens in the presence and absence of extracellular quinones. Environ Microbiol 4: 115-124.

36. Kumaraswamy S, Ramakrishnan B, Sethunathan N (2001) Methane production and oxidation in an anoxic rice soil as influenced by inorganic redox species. J Environ Qual 30: 2195-2201.

37. Tiedje JM, Sexstone AJ, Myrold DD, Robinson JA (1982) Denitrification: ecological niches, competition and survival. Antonie Van Leeuwenhoek 48: 569-583.

38. Carucci A, Kuhni M, Brun R, Carucci G, Koch G, et al. (1999) Microbial competition for the organic substrates and its impact on EBPR systems under conditions of changing carbon feed. Water Sci Technol 39: 75-85.

39. Paul JW, Beauchamp EG, and Trevors JT (1989) Acetate, propionate, butyrate, glucose, and sucrose as carbon sources for denitrifying bacteria in soil. Can J Microbiol 35:754-759.

40. Bodegom PV, Goudriaan J, Leffelaar P (2001) A Mechanistic Model on Methane Oxidation in a Rice Rhizosphere. Biogeochemistry 55: 145-177.

41. Henckel T, Roslev P, Conrad R (2000) Effects of O2 and CH4 on presence and activity of the indigenous methanotrophic community in rice field soil. Environ Microbiol 2: 666-679.

42. Kimura M, Miura Y, Watanabe A, Murase J, Kuwatsuka S (1992) Methane production and its fate in paddy fields. Soil Sci Plant Nutr 38: 665-672.

43. Murase J, Kimura M (1996) Methane production and its fate in paddy fields. Soil Sci Plant Nutr 42: 187-190.

44. Cole CV, Duxbury J, Freney J, Heinemeyer O, Minami K, et al. (1997) Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutr Cycl Agroecosys 49: 221-228.

45. Conrad R (1996) Soil microorganisms as controllers of atmospheric trace gases (H2, CO, CH4, OCS, N2O, and NO). Microbiol Rev 60: 609-640.

46. Neue HU, Ziska LH, Matthews RB, Dai Q (1995) Reducing Global Warming - The Role of Rice. GeoJournal 35: 351-362.

47. Wassmann R, Papen H, Rennenberg H (1993) Methane emission from rice paddies and possible mitigation strategies. Chemosphere 26: 201-217.

48. Adhya TK, Patnaik P, Rao VR, Sethunathan N (1996) Nitrification of ammonium in different components of a flooded rice soil system. Biol Fertil Soils 23: 321-326.

49. Lindau CW, Bollich PK, DeLaune RD, Mosier AR, Bronson KF (1993) Methane mitigation in flooded Louisiana rice fields. Biol Fertil Soils 15: 174-178.

50. Semrau JD, DiSpirito AA, Yoon S (2010) Methanotrophs and copper. FEMS Microbiol Rev 34: 496-531.

51. Hanson RS, Hanson TE (1996) Methanotrophic bacteria. Microbiol Rev 60: 439-471.

52. Bouwman AF (1990) Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. Soils and the Greenhouse Effect, J. Wiley & Sons Ltd, USA

53. Crutzen PJ (1991) Methane's sinks and sources. Nature 350: 380-381.

54. Kirschbaum MUF (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biol Biochem 27: 753-760.

55. Pearman GI, Fraser PJ (1988) Sources of increased methane. Nature 332: 489-490.

56. Cicerone RJ, Oremland RS (1988) Biogeochemical aspects of atmospheric methane. Global Biogeochem Cycles 2: 299-327.

57. Lynch JM (1978) Production and phytotoxicity of acetic acid in anaerobic soils containing plant residues. Soil Biol Biochem 10: 131-135.

58. Yamane I, Sato K (1963) Decomposition of organic acids and gas formation in flooded soil. Soil Sci Plant Nutr 9: 32-36.

59. Topp E, Pattey E (1997) Soils as sources and sinks for atmospheric methane. Can J Soil Sci 77: 167-177.

60. Lovley DR (1987) Organic matter mineralization with the reduction of ferric iron: A review. Geomicrobiology Journal 5: 375-399.

61. Fox BG, Froland WA, Dege JE, Lipscomb JD (1989) Methane monooxygenase from Methylosinus trichosporium OB3b. Purification and properties of a three-component system with high specific activity from a type II methanotroph. J Biol Chem 264: 10023-10033.

62. Colby J, Stirling DI, Dalton H (1977) The soluble methane mono-oxygenase of Methylococcus capsulatus (Bath). Its ability to oxygenate n-alkanes, n-alkenes, ethers, and alicyclic, aromatic and heterocyclic compounds. Biochem J 165: 395-402.

63. Fogel MM, Taddeo AR, Fogel S (1986) Biodegradation of chlorinated ethenes by a methane-utilizing mixed culture. Appl Environ Microbiol 51: 720-724.

64. Oldenhuis R, Vink RL, Janssen DB, Witholt B (1989) Degradation of chlorinated aliphatic hydrocarbons by Methylosinus trichosporium OB3b expressing soluble methane monooxygenase. Appl Environ Microbiol 55: 2819-2826.

65. Alvarez-Cohen L, McCarty PL (1991) Product toxicity and cometabolic competitive inhibition modeling of chloroform and trichloroethylene transformation by methanotrophic resting cells. Appl Environ Microbiol 57: 1031-1037.

66. Chang HL, Alvarez-Cohen L (1996) Biodegradation of individual and multiple chlorinated aliphatic hydrocarbons by methane-oxidizing cultures. Appl Environ Microbiol 62: 3371-3377.

67. Lontoh S, Semrau JD (1998) Methane and Trichloroethylene Degradation by Methylosinus trichosporium OB3b Expressing Particulate Methane Monooxygenase. Appl Environ Microbiol 64: 1106-1114.

68. Melse RW, Van der Werf AW (2005) Biofiltration for mitigation of methane emission from animal husbandry. Environ Sci Technol 39: 5460-5468.

69. Lee SW, Keeney DR, Lim DH, Dispirito AA, Semrau JD (2006) Mixed pollutant degradation by Methylosinus trichosporium OB3b expressing either soluble or particulate methane monooxygenase: can the tortoise beat the hare? Appl Environ Microbiol 72: 7503-7509.

70. Lontoh S, Zahn JA, DiSpirito AA, Semrau JD (2000) Identification of intermediates of in vivo trichloroethylene oxidation by the membrane-associated methane monooxygenase. FEMS Microbiol Lett 186: 109-113.

71. Nikiema J, Bibeau L, Lavoie J, Brzezinski R, Vigneux J, et al. (2005) Biofiltration of methane: An experimental study. Chemical Engineering Journal113: 111-117.

72. Etheridge DM, Steele LP, Francey RJ, Langenfelds RL (1998) Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climatic variability. J Geophys Res 103: 15979-15993.

73. Le Mer J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: a review. European Journal of Soil Biology 37: 25-50.

74. Blaha D, Barrtlett K, Czepiel P, Harris R, Crill P (1999) Natural and anthropogenic methane sources in New England. Atmospheric Environment 33: 243-255.

75. Bousquet P, Ciais P, Miller JB, Dlugokencky EJ, Hauglustaine DA, et al. (2006) Contribution of anthropogenic and natural sources to atmospheric methane variability. Nature 443: 439-443.

76. le Texier H, Solomon S, Garcia RR (1988) The role of molecular hydrogen and methane oxidation in the water vapour budget of the stratosphere. Quarterly Journal of the Royal Meteorological Society 114: 281-295.

77. Wahlen M (1993) The Global Methane Cycle. Ann Rev Earth Planet Sci 21: 407-426.

78. Sundh I, Mikkela C, Nilsson M, Svensson BH (1995) Potential aerobic methane oxidation in a Sphagnum-dominated peatland-Controlling factors and relation to methane emission. Soil Biology and Biochemistry 27: 829-837.

79. Borjesson G, Sundh I, Tunlid A, Svensson BH (1998) Methane oxidation in landfill cover soils, as revealed by potential oxidation measurements and phospholipid fatty acid analyses. Soil Biology and Biochemistry 30: 1423-1433.

80. Roberts AP, Mount AS, Seda B, Souther J, Qiao R, et al. (2007) In vivo biomodification of lipid-coated carbon nanotubes by Daphnia magna. Environ Sci Technol 41: 3025-3029.

81. Fernandes TF, Christofi N, Stone V (2007) The Environmental Implications of Nanomaterials, in Nanotoxicology: Characterization, Dosing, and Health Effects 456.

82. Lynch I, Dawson KA, Linse S (2006) Detecting cryptic epitopes created by nanoparticles. Sci STKE 2006: pe14.

83. Rothen-Rutishauser BM, Schürch S, Haenni B, Kapp N, Gehr P (2006) Interaction of fine particles and nanoparticles with red blood cells visualized with advanced microscopic techniques. Environ Sci Technol 40: 4353-4359.

84. Smart SK, Cassady AI, Lu GQ, Martin DJ (2006) The biocompatibility of carbon nanotubes. Carbon 44: 1034-1047.

85. Limbach LK, Li Y, Grass RN, Brunner TJ, Hintermann MA, et al. (2005) Oxide nanoparticle uptake in human lung fibroblasts: effects of particle size, agglomeration, and diffusion at low concentrations. Environ Sci Technol 39: 9370-9376.

86. Chithrani BD, Ghazani AA, Chan WC (2006) Determining the size and shape dependence of gold nanoparticle uptake into mammalian cells. Nano Lett 6: 662-668.

87. Klaine SJ, Alvarez PJ, Batley GE, Fernandes TF, Handy RD, et al. (2008) Nanomaterials in the environment: behavior, fate, bioavailability, and effects. Environ Toxicol Chem 27: 1825-1851.