Strategies for combating nitrate pollution

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Nitrate leaching is a global phenomenon. Nitrate contamination of drinking water leads to a number of health problems to human beings and animals. In the context of the challenge of increasing food production with decreasing cultivable lands demanding heavy application of nitrogen leading to increased nitrate leaching, strategies for reducing it are discussed. The need for measuring nitrates, and methods of measurement of nitrates are discussed. The need for modelling and for long term studies is emphasized. Management options to reduce nitrate leaching from agricultural lands, remedial measures available for removing the nitrates after contamination has occurred and nitrate leaching from organic farming, and finally, some special studies aimed at guiding policy makers are discussed. The status of nitrate contamination in the country is briefly described.

Keywords: Drinking water, nitrogen, nitrate pollution.

PRODUCING an adequate quantity of healthy food without polluting the environment is a formidable challenge for future agriculture in the world[1]. About 260 million tonnes of atmospheric nitrogen is being fixed every year globally[2]. The global mean N use efficiency is estimated to be about 50% (ref. 3). The remaining quantity of nitrogen is lost into the environment. A large proportion of this nitrogen gets converted into nitrate which, being soluble in water and not retained by soils, gets leached into water bodies. Leaching of nitrate from agricultural land and from other sources to groundwater is a global phenomenon. Groundwater is the major source for drinking purposes. Nitrates in drinking water is associated with a number of health problems such as methemoglobinemia, oral cancer, cancer of the colon, rectum and other gastrointestinal cancers, Alzheimer's disease, vascular dementia, absorptive, secretive functional disorders of the intestinal mucosa, changes in the maturation, differentiation and apoptosis in intestinal crypts, multiple sclerosis, reduced casein digestion, neural tube defects, cytogenetic effects in children, Non-Hodgkin's lymphoma, hypertrophy of thyroid, development of tolerance (lowering of response) to nitrate drugs and recurrent stomatitis in human beings and methaemoglobinemia in ruminants and severe gastritis in monogastric animals, intestinal disorders in pigs, pregnancy-related disorders in rats, depression, muscle tremors and incoordination in goats, loss of body weight and reduced water consumption in chickens, sexual disorders in sheep and hyperthyroid in foals[4]. Methaemoglobinemia was found prevalent in all age groups in areas of Rajasthan, with high nitrate concentrations in drinking water[5]. Recurrent acute respiratory tract infections in some areas of Rajasthan have been attributed to high nitrate concentrations in drinking water[6]. Non-agricultural sources of groundwater nitrate have been discussed in a recent review[7]. In the context of facing the challenge of increasing food production from decreasing cultivable land, issues concerned with nitrate pollution in this country and elsewhere are reviewed and policy options available for combating the problem are discussed in this paper.

Measurement of nitrate leaching

In order to generate sufficient data for providing the basis for forming policies, nitrate leaching must be measured under a wide variety of situations. Temporal and spatial analysis of the data so obtained will help in identifying trends, sources of contamination and vulnerable zones. There are several approaches for the measurement of nitrate leaching and these have been reviewed[4]. Direct measurements using lysimeters, porous cups, suction, capillary passive samplers and resin capsule methods, as well as indirect methods such as chloride balance, field measurements of hydraulic water gradients and hydraulic conductivity have been used with various degrees of success but the lysimeter method is regarded as the most reliable one. Pan samplers need estimation of their collection efficiency. The resin capsule is a promising technique for nitrate measurements. A flow proportional drainage water sampling method is available for accurate estimation of cumulative leaching from submerged drains[8]. Isotope techniques (using ^{2}H, ^{18}O, etc.) can give direct insight into water cycle, soil water management, groundwater flow regime, recharge and contamination characteristics, residence time (age) in the aquifer, groundwater–surface water interactions, groundwater hydrodynamic zones, flow-pathways and mixing processes in groundwater system[9]. More field research is

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needed on isotopic responses and dynamics of pollutants in the groundwater flow, aquifer's attenuation capacity for contaminants under natural and exploited conditions. Vulnerability can be minimized or controlled by planned groundwater abstraction, strict regulatory enforcement to eliminate waste disposal within the protection zones and harmonizing need and long term actions. To optimize the extraction of information from nitrate measurements, mathematical models can be used.

Models for nitrate leaching

Mathematical models are useful for the study of nitrate leaching because of their predictive capability. Models are portable in the sense that they are adaptable to different situations after adjusting the model parameters accordingly. They also allow better understanding of the interdependency of the relevant parameters and permits identification of sensitive input parameters. Expert systems can be developed to quickly formulate efficient fertilizer recommendations and help in maintaining accurate records. In order to understand the factors involved and to predict the effect of changes in management of land on nitrate leaching, a number of models of nitrate leaching have been developed and tested. For example, 'Parameter ESTimation' (PEST) programme has been used to calibrate soil physical parameters of a nitrate leaching model (the Burns alpha model)[10]. Some of the models were combined with remote sensing to enhance their capabilities. For example, by coupling Geographical Information System (GIS) with groundwater loading effects of agricultural management systems (GLEAMS), nitrate leaching maps were obtained by Pazand Ramos (2004) for different nitrogen rates[11]. The GIS-GLEAMS system was a useful tool to assess the N leaching at a regional scale for different N management practices. A temporal analysis identified the influence of soil nitrate concentrations and rainfall on nitrate leaching. Nitrate concentrations in soil up to 60–90 cm deep have been detected through satellite images[12]. The combined use of a simulation model, grain yield and nitrate leaching response functions could be applied in decision support systems and improve the N management on field scale to optimize grain yields and minimize nitrate leaching risk[13]. The integrated soil–crop–atmosphere model 'Water and Agrochemicals in the Vadose Environment (WAVE)' gave good predictions but more studies were needed combining with its crop growth model[14]. Ruelle *et al.*[15] in France used NIWASAVE, a model simulating the impact of water application depths on crop yields and nitrate leaching to show that a 20% reduction in nitrogen fertilizer application results in an average yield reduction of only 0.1 t/ha. A Fuzzy Nitrogen Balance (FuN-Balance) model has been developed for field-specific determination of nitrate concentrations of percolating water in agricultural catchments[16]. Peralta and Stockle[17] made a long-term simulation study in Washington, USA, on nitrate leaching under irrigated potato rotation using a cropping systems model (Crop Syst) to simulate the interactions among soils, crops, weather, and irrigation and fertilizer application management. Their results showed that reducing fertilizer application rates was the only effective approach to reduce nitrate leaching. Artificial neural networks have been used for simulating nitrate leaching[18]. Of the total amount of applied fertilizers (138 Tg year^{-1}), 19% was lost to nitrate leaching, 8% to gaseous ammonia and 3% to gaseous nitrogen oxides and the rest was assumed to be fixed in the ecosystem through vegetation uptake[19]. To study the movement and nitrate leaching in structured soils where macroporosity manipulated by tillage operations, strongly influences these processes, a model specific to these soils, Crack-P was developed[20]. The results from both the model and the field data demonstrated that finer soil structures release more nitrates through drainage waters. Tripathi *et al.*[21] used Soil and Water Assessment Tool (SWAT) model to develop effective management plan for identified critical sub watersheds of Nagwan, located in eastern part of India. Taking into consideration sediment yield and nutrient losses, the conventional tillage (as against zero and conservation tillage) was considered the best. Optimum clay barrier thickness required to prevent migration of contaminants to the aquifer located below could be determined using the model. At present 40 researchers from across the country are learning Mathematical Modelling of Groundwater Quality and Pollution at DST SERC School, Bangalore. The Centre for Advanced Studies in Fluid Mechanics, Department of Mathematics, Bangalore University was chosen to train 40 researchers every year for a period of five years. Therefore, we may expect more modelling studies on nitrate contamination of groundwater in our country in the coming years. The results of such models throw light on measures that could lead to reduction in nitrate leaching and thus facilitate government advisers and extension workers. Though models can be used to predict the consequences of land and crop management, such predictions can only be verified by actual long-term measurements.

Long-term studies

Long-term studies allow correlations to be made between changes in land and crop managements, weather and pollution levels. Results based on long-term studies can be accepted with a high level of confidence. Long-term studies have been carried out in many countries and these have provided a rich source of knowledge on which strategies for reducing nitrate pollution can be based. Effect of different cropping systems, fertilizer and other agronomical practices, soil type, climate, etc. on nitrate leaching should be quantitatively studied in India. A case study on environmental consequences of agricultural development in Haryana, India has been made and this has showed that nitrate contamination of groundwater is on the rise[22]. Reduction of fertilizer application cannot be considered for food crops in India since maximizing food production is the top priority for food and nutritional security of the population. A number of other management options may be considered instead. Apart from agriculture, forests can also contribute to nitrate pollution and this has to be monitored. Borken and Matzner[23] showed that forest soils with C : N ratio <25 released significantly more nitrate when nitrogen deposits remain on a high level. Wachendorf *et al.*[24] conducted a 4-year study on nitrate leaching from grassland and concluded that N fertilizer application policy for grassland has to be revised and grazing intensity has to be reduced by integrating silage cuts. In a 15-year study in Indiana, USA, Kladivko *et al.*[25] found that most nitrate losses occurred during the fallow season, when most of the drainage occurred. The study clearly demonstrated the effect of reducing fertilizer application as well as that of a winter cover crop in minimizing nitrate loss. There is a need for such long-term research on different soil types and climates to develop appropriate management strategies for both economic crop production and environmental quality. Wakida and Lerner[26] recommended stripping of topsoil from construction sites to reduce nitrate leaching because the topsoil contains most of the potentially mineralizable nitrogen. Stauffer and Spiess[27] studied the difference of six crop rotations for seven years and found significant differences and suggested that sequence of crops should receive more attention with respect to nitrate leaching. Goulding *et al.*[28] showed that some drainage waters exceeded EU limit of 11.3 mg nitrate N per litre when rain followed a dry summer and autumn, even from some plots of Broadbalk experimental at Rothamsted, UK that received no fertilizer. This shows that nitrate contamination can occur even when no fertilizers are applied. Thus, there can be many reasons for nitrate pollution and it is necessary to identify them for developing strategies to minimize them.

Management options to reduce nitrate leaching from agriculture

Among the various options available to reduce nitrate leaching are cover crops, using specific management practices, use of nitrification inhibitors or controlled-release fertilizers, site-specific crop management, variable rate application, proper scheduling of irrigation, sprinkler or drip irrigation with fertigation, banding and split application, chlorophyll measurement or colour chart based nitrogen application, foliar application, etc.[29–34]. According to Baker[35], it is not realistic to expect reductions in nitrate leaching greater than 25 to 30% within field practices alone and if this reduction is insufficient, additional off-site landscape modification is necessary.

Enhancing fertilizer N use efficiency by ensuring measures such as balanced application of nutrients, proper coordination of N and irrigation management and site-specific and need-based nutrient management can substantially control the leaching of nitrate N beyond root zone of crops[36]. There can be two general approaches to minimize environmental pollution arising due to N use in agriculture: one is the optimum use of the ability of crop plants to compete with other processes which lead to the losses of N from soil plant system to the environment and the other is the direct reduction of the rate, duration and extent of loss through the loss processes themselves.

Balanced application of N, P and K can significantly reduce the amount of unutilized nitrate in the root zone. Ways to increase N use efficiency in rice–wheat crop systems have been discussed[37]. Vegetation retards nitrate leaching from root zone by absorbing nitrate and water. Rooting habits of plants exert a profound influence on nitrate mobility in the root zone. Maximum leaching of nitrate below the root zone occurs from crop rotations with heavily fertilized shallow rooted crops like potato. However, wheat, when grown in a rotation absorbs a large fraction of the applied N due to its deep rooting system. Optimum rates of fertilizer N are those that result in yields only slightly below the maximum but N use efficiency is high and unutilized N is low. Nitrogen contained in irrigation water must be taken into account when calculating the N requirement of the crop.

Remedial measures

Since nitrate leaching cannot be totally avoided in most cases one can think of either using the nitrate containing water for irrigation purposes or use of some kind of remediation technique to remove the nitrate ions before using the water for drinking. A comprehensive account of methods and techniques used for nitrate removal from water has been published[38]. Remediation techniques include water table adjustments to increase denitrification, bioremediation using *Pseudomonas* and *Bacillus*, aquatic plants like *Lemma*, *Wolffia*, urticularia and pteridophites, bank filtration, etc. Recently, quaternized biomass has been proposed as an ion exchanger for removing nitrate and other anions from water[39].

Nitrate leaching and organic farming

Although some enthusiasts of organic farming claim that nitrate leaching is eliminated in organic farming, it is necessary to experimentally determine the extent of leaching of nitrate from organic farms. According to one review, nitrate leaching was not a question of organic or conventional farming but rather of introducing and use of appropriate counter measures[40]. Stoppes *et al.*[41] made a comparison between organic and conventional farming and found that nitrate losses from arable crops averaged 47 and 58 kg N ha^{-1} for organic and conventional farming systems respectively, and concluded that under similar cropping, losses from organic systems are similar or slightly smaller than those from conventional farms following best practice. Kirchmann *et al.*[42] proposed the following guidelines to minimize leaching from agricultural soils: (1) environmental indexing of fields and consideration of spatial variability within a catchment, (2) reduction of nitrate inputs to soils to levels slightly below those expected to give optimum yield by applying less nitrogen fertilizer and by further reduction in animal density, and (3) use of a range of counter measures: Catch crops, minimum tillage, control of biological processes, etc. It has been reported that bare fallow in organic farming practices leads to increased leaching[43]. Guarda *et al.*[44] stated that even under organic farming practices the best practice is not to employ old populations or varieties but to use modern cultivars because they had intrinsic traits capable of ensuring yield and quality at low nitrogen supply even though they maximize their traits at high nitrogen inputs. Leaching of organic nitrogen compounds from organic farms is also a concern since mineralization can take place after leaching. In the emerging scenario of organic farming in India, nitrogen leaching losses have to be assessed and appropriate measures have to be taken, on a case to case basis, to minimize the losses.

Forests can also contribute to nitrate leaching in various ways. Edge effect in forests where aerosol nitrogen is collected and then leached down by rain has been studied in Germany[45]. Contribution of nitrate to the pollution of drinking water sources from sources such as the above need to be assessed.

Studies aimed at providing information to policy makers

Some studies have been made outside India with the aim of providing information useful for policy makers and these can serve as examples for research workers in India. Sumelius *et al.*[46] made a study of maize cultivation in Croatia. At profit maximizing levels of nitrogen application nitrate leaching was unacceptably high. 'Maximum abatement cost' (MAC) was calculated which showed that 76% reduction in nitrate leaching can be achieved by one of the three options: a tax on optimal N doses, a product tax and a fertilizer quota. It was concluded that a quota had the lowest MAC in this case. van der Hoek[47] presented nitrogen balance sheets for animal production system, crop production system and agricultural sector as a whole for European Union and Indian subcontinent[47]. The balance sheet for crop production and agricultural sector as a whole showed a surplus of 60 kg nitrogen per hectare. Nitrate can also be removed from water by establishing wetlands and biofilters. Public must be educated about the complexity of the problem and need for multiple management strategies. Reinhard and Tijssen[48] used a 'shadow cost system approach' to analyse the cost efficiency and nitrogen efficiency of Dutch dairy farms and showed that for optimal mix of variable nitrogen sources, the mean nitrogen efficiency was 56% and the nitrogen surpluses would be half the observed one whereas the production cost would go up by only 3%. Studies like this should be undertaken in India for assisting policy makers. Institutional mechanisms to deal with pollution in agricultural sector are lacking in India. The goal of sustainable land use can be achieved through education, training and research. Research institutes and NGOs must work together with land users and communities. The corporate sector can also play a role in bringing about the necessary changes in the use of natural resources in a more sustainable manner. A report of a research study conducted in Sweden on economical, environmental and social aspects of sustainable farming systems concluded thus: a range of sustainable solutions exist involving government policies including subsidies, research and technology and public acceptance of farming practices[49]. Participatory approach to knowledge transfer is needed, in which scientists, policymakers, farmers, advisors and consumers exchange information and together build sustainable farming systems.

Current status of nitrate pollution in India

There is insufficient data for making categorical statements on the status of nitrate pollution in India. A recent publication indicated that nitrate in groundwater was in the range 0.1–870 mg/l with an average of 65 mg/l[50]. Gujarat, Rajasthan and West Bengal were the states with high nitrate content in groundwater. A World Bank-assisted study in Karnataka showed that nitrate contamination of groundwater was a problem in a majority of districts[51]. In the year 2000, it has been reported that more than 33% of water samples in Punjab and Haryana had nitrate levels above the desired limits[52]. Instances of high concentrations of nitrate in groundwater in most parts of the country, with the exception of Jammu, Kashmir and the north eastern states, are being reported.

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