

Modeling Nitrogen Mineralization Kinetics in Arable Soils of Semiarid India

HARMANJIT SINGH HAER
DINESH KUMAR BENBI

Department of Soils
Punjab Agricultural University
Ludhiana, India

Laboratory incubation experiments were conducted to study N mineralization kinetics in 15 benchmark soils of Punjab, India. Aerobic incubations were carried out for 112 days at 32°C and –33 kPa water potential. Cumulative N mineralization in different soils ranged from 8.2 to 75.6 mg kg^{–1} soil, which constituted 2.7 to 8.8% of soil organic N. For each gram of organic carbon (OC) kg^{–1} soil, about 9 mg N was mineralized in 112 days of incubation. Mineralization was faster during initial days of incubation followed by a relatively slower rate subsequently. Kinetic models of varying complexity were fitted to N mineralization vs. time data. The first-order single compartment (FOSC) model provided relatively poor fit to the data and systematically deviated from the measured values. Both the first-order double compartment (FODC) and the first-order zero-order (FOZO) models provided good fit to the data and yielded very low residual mean squares. In soils with OC content > 0.55%, the FODC model invariably provided the best fit. It was concluded that a minimum of two pools of organic matter may be considered to contribute towards organic N mineralization in these soils. Soil OC and clay strongly influenced the FOSC- and FODC-predicted N mineralization potential of soils. A linear regression involving OC and clay × OC interaction could be used to predict N mineralization potential of the soils.

Keywords kinetic models, organic carbon, organic matter-N interactions, camborhids, eutrochrepts, haplustalfs, ustochrepts, ustipsamments

Nitrogen use efficiency in terms of plant uptake is generally low and varies greatly under different cropping conditions. The unrecovered N is prone to losses through leaching and denitrification, leading to environmental problems such as ground water contamination, eutrophication, global warming, and acid rain. A major constraint in improving fertilizer N use efficiency is the inability to determine reliably the magnitude and dynamics of soil N supply (Jarvis et al., 1996). Problems arise partly from the fact that both the soil organic N and the microbes that mineralize N are poorly characterized. The situation is exacerbated by the fact that a number of soil and environmental conditions control the rates and products of mineralization

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Address correspondence to Dr. Dinesh K. Benbi, Department of Soils, Punjab Agricultural University, Ludhiana 141 004, India. E-mail: dbenbi@sify.com

(Seyfried & Rao, 1988). Among the environmental variables, temperature and moisture are the most important factors that exert influence on N mineralization rates in soils (Ellert & Bettany, 1992; Goncalves & Carlyle, 1994; Zak et al., 1999). The important soil factors that dictate N mineralization kinetics include organic matter quality and content, microbial biomass, and soil texture (Cambardella & Elliott, 1992; Hassink et al., 1990; Curtin et al., 1999; Verberne et al., 1990). Most of the studies on N mineralization kinetics reported in literature have been conducted on soils of humid and subhumid regions, which have developed under low temperature and high moisture conditions and the soils are generally low in pH and rich in organic matter. There is less information available on soils of arid and semiarid, subtropical regions.

Kinetic models of varying complexity, ranging from zero-order (Addiscott, 1983) through single compartment first-order (Stanford & Smith, 1972) to multi-compartment first-order (Molina et al., 1980; Nuske & Richter, 1981), have been used to describe net N mineralization in soils. For a review of the modeling approaches see Benbi and Richter (2002). The suitability of a given model to describe N mineralization kinetics has been found to depend on soil type and the experimental conditions prior to and during incubation. However, the performance of different kinetic models on soils of arid and semiarid regions is not known. The present studies were therefore conducted to (a) study N mineralization kinetics of a number of arable soils of semiarid Punjab, India, (b) evaluate different models for describing net N mineralization in these semiarid soils, and (c) study the relationship between soil properties and N mineralization potential of soils.

Materials and Methods

Bulk soil samples were collected from benchmark sites in the northwestern state of Punjab, India. The sampling sites (located between 29°30' and 32°32' N latitudes and 73°55' and 76°55' E longitudes) have a subtropical, semiarid, and monsoonal climate with topography varying from sand dunes to piedmont plains. An intensive and irrigated agriculture is followed in this region, which is a major contributor to the country's cereal pool. The average monthly air temperature ranges between 13°C in January and 34°C in June. Annual rainfall ranges from 1250 mm in the north to 350 mm in the southwest. More than 70% of the annual rainfall occurs during the monsoon season from July to September. The soils of the region are generally coarse textured, alluvial, poor in organic matter content (<1%) and neutral to alkaline in pH. Soil moisture regimes are udic, ustic, and aridic whereas soil temperature regime is mainly hyperthermic. The sampling sites representing Ballawal, Chamror, Dhar, and Jassi Powali soil series are rainfed, whereas all the other sites are irrigated by ground- and surface water. The prevalent cropping system at different sampling sites is either rice-wheat (Ladhowal, Fatehpur, Ghabdan, Gurdaspur, Nabha, Kanjli, and Naura), rice-berseem (Sadhugarh), cotton-wheat (Jassi Powali, Gehri Bhagi, and Abohar), maize-wheat (Ballawal, Chamror, and Zirakpur) or maize fodder-wheat (Dhar). General fertilizer management practices include application of 120 kg N ha⁻¹ (through diammonium phosphate and urea) to irrigated rice, maize, and wheat, and 75 kg N ha⁻¹ to cotton. For rainfed crops, the fertilizer dose is reduced to 80 kg N ha⁻¹ for maize and wheat and 50 kg N ha⁻¹ for cotton. In addition to N fertilizers, P and K are applied on soil test basis.

Surface soil samples (top 15 cm), representing 15 soil series varying in soil organic carbon (OC) and texture were collected from cultivated fields at harvest of post rainy season crop in the months of October and November. The samples were

air-dried and ground to pass through a 2 mm sieve before being used in laboratory incubation studies. The soil samples were analyzed for particle size distribution by international pipette method (ISSS, 1929), pH (1:2 soil:water suspension with a glass electrode), OC by wet digestion (Walkley & Black, 1934), total N by digesting in concentrated H_2SO_4 (Bremner & Mulvaney, 1982) and mineral N by steam distillation method (Keeney, 1982). Organic N in soil samples was calculated as the difference between total and mineral N contents. The soils ranged from sandy loam (sl) to clay loam (cl) in texture, 0.17 to 0.82% OC, 330 to 1430 mg total N kg^{-1} soil and 28 to 140 mg mineral N kg^{-1} soil (Table 1).

Mineralization of organic N was studied in the laboratory by conducting aerobic incubation under controlled conditions. Thirty grams of air-dried, ground and sieved (<2 mm) soil were taken in cylindrical wide-mouthed plastic vials (capacity 50 mL) in triplicate. The soils were wetted to -33 kPa potential (estimated by using pressure plate apparatus). The vials were capped and a few pinholes in the caps were made for aeration. The soil samples were incubated for 0, 1, 3, 6, 9, 14, 28, 42, 56, 70, 84, 98, and 112 days in a biological oxygen demand (B.O.D.) incubator at 32°C and -33 kPa water potential. Soil water content was maintained by weighing the containers alternate days and replenishing the water lost. Independent sets for each incubation period were maintained to avoid soil disturbance during sampling. At the end of each incubation period, whole soil in a vial was shaken with 1 M KCl (soil: solution ratio of 1:7.5) for 1 hour. The extract was filtered (through Whatman No. 1 filter paper) and NH_4^+ -N and NO_3^- -N in the filtrate was determined by steam distillation method (Keeney, 1982). The amount of N mineralized (NH_4^+ -N + NO_3^- -N) at a given time, t , was calculated by subtracting mineral-N content (NH_4^+ -N + NO_3^- -N) of the soil at the start of incubation from mineral N at time, t .

The time course of N mineralized was fitted to different kinetic models (Table 2) using nonlinear least squares technique. These models predict net N mineralization and do not consider the process of ammonification and nitrification separately. The first-order single compartment (FOSC) model (Equation 1, Table 2) is based on the assumption that the rate of N mineralization is proportional to the size of the mineralizable pool ($\text{dN}/\text{dt} = -k\text{N}$) termed as N mineralization potential (N_o) (Stanford & Smith, 1972). Several authors (Molina et al., 1980; Nuske & Richter, 1981; Deans et al., 1986) have proposed that more than one fraction of soil organic N may be directly mineralized, each with its specific rate of decomposition. In the simplest form of the multifraction approach, two main fractions of organic N are assumed to mineralize at different rates (Nuske & Richter, 1981; Nordmeyer & Richter, 1985; Deans et al., 1986), following first-order kinetics (FODC model Equation 2, Table 2). One fraction consists of N compounds of easily decomposable plant material (dpm), while the second fraction represents the more resistant or recalcitrant plant material (rpm). The dpm fraction mineralizes at a faster rate than the rpm fraction. Beauchamp et al. (1986) argued that the relatively fast mineralizable fraction may be a consequence of drying and subsequently rewetting the soil rather than due to N mineralization from a separate soil organic N fraction. They (Beauchamp et al., 1986) modified the FOSC model to account for this "artifact mineralization" (Equation 3, Table 2).

The single and multifraction first-order kinetic models are based on the assumption that the N mineralization potential of soil is a definable quantity and may be quantified from short-term or long-term incubations. However, many researchers have suggested that, with the incubation methods, it may not be possible to define the N mineralization potential of soils because the slowly mineralizable N fraction may in fact follow zero-order kinetics (Bonde & Rosswall, 1987; Lindemann et al., 1988; Seyfried & Rao, 1988). They advocated the use of mixed first-order and zero-order (FOZO) kinetic model (Equation 4, Table 2).

The use of empirically determined equations such as polynomials and parabolic functions has been proposed to describe net N mineralization in soils (Broadbent,

TABLE 1 Selected Physicochemical Properties of the Experimental Soils

Sr No.	Benchmark soil series	Soil taxonomic classification ^a	Texture	Soil separates			Organic carbon (g kg ⁻¹)	Total N (mg kg ⁻¹)	Organic N (mg kg ⁻¹)	Mineral N (mg kg ⁻¹)
				Sand (%)	Clay (%)	pH				
1	Jassi Powali	Ustic Torripsamments	Sandy loam (sl)	72	18	8.2	1.7	330	302	28
2	Ghabdan	Typic Natrustalfs	Sandy clay loam (scl)	60	25	9.7	1.9	297	247	50
3	Ballawal	Typic Ustipsamments	Sandy loam (sl)	70	15	7.9	2.0	360	331	29
4	Ladhowal	Typic Ustifluvents	Sandy loam (sl)	62	10	7.7	2.8	408	376	32
5	Fatehpur	Typic Ustipsamments	Sandy loam (sl)	76	14	7.7	3.4	440	398	42
6	Nabha	Typic Ustochrepts	Sandy loam (sl)	70	20	8.0	4.0	630	595	35
7	Gehri Bhagi	Ustochreptic Camborthids	Sandy clay loam (scl)	70	21	8.1	4.0	605	577	28
8	Kanjli	Typic Ustochrepts	Sandy loam (sl)	70	20	7.8	5.5	660	640	20
9	Chamror	Dystic Eutrochrepts	Sandy clay loam (scl)	46	27	7.0	5.5	880	820	60
10	Naura	Typic Haplustalfs	Silty clay loam (scl)	18	34	7.6	5.7	1247	1107	140
11	Abohar	Ustochreptic Camborthids	Sandy clay loam (scl)	50	26	8.1	6.3	902	805	97
12	Sadhugarh	Vertic Ustochrepts	Clay loam (cl)	35	35	8.2	6.6	800	777	23
13	Gurdaspur	Typic Haplustalfs	Silt loam (sil)	17	23	6.8	7.3	1243	1217	26
14	Zirakpur	Aquic Ustorthents	Loam (l)	52	15	7.8	7.3	1100	1014	86
15	Dhar	Typic Eutrochrepts	Loam (l)	50	20	7.8	8.2	1430	1402	28

^aTaxonomy according to USDA classification system (Soil Survey Staff, 1999).

TABLE 2 Kinetic Models Fitted to N Mineralization Data

Equation no.	Model	Equation	Reference
1	First-order single compartment (FOSC)	$N_t = N_o(1 - e^{-k_t t})$	Stanford & Smith (1972)
2	First-order double compartment (FODC)	$N_t = N_d(1 - e^{-k_d t}) + N_r(1 - e^{-k_r t})$	Molina et al. (1980); Nuske & Richter (1981)
3	First-order zero order (FOZO)	$N_t = N_d(1 - e^{-k_d t}) + Kt$	Seyfried & Rao (1988)
4	Modified first order (MFO)	$N_t = N_o - (N_o - N_e)e^{-k_t t}$	Beauchamp et al. (1986)

N_t = cumulative N mineralized (mg kg^{-1}) at time “ t ” (days).
 N_d = readily decomposable organic N fraction (mg kg^{-1}).
 N_r = recalcitrant organic N fraction (mg kg^{-1}).
 N_e = intercept on the Y-axis (mg kg^{-1}).
 N_o = N mineralization potential (mg kg^{-1}).
 k_d , k_r = first-order rate constants (day^{-1}).
 K = zero-order rate constant (day^{-1}).

1986; Marion & Black, 1987). Broadbent (1986) found that the parabolic function (Equation 5) provided a good fit to the data from a number of published studies:

$$N_t = at^b, \quad (5)$$

where N_t is cumulative N mineralized after time t , and a and b are regression coefficients.

Different models were compared with respect to goodness of fit to the experimental data as indicated by the residual mean squares (RMS). The statistical significance of differences in the residuals between any two models was assessed by F -test (Beck & Arnold, 1977; Robinson 1985). Regression analysis was performed to study the relationship between N mineralization potential (N_o) estimated by FOSC and FODC models, and other soil properties.

Results and Discussion

Nitrogen Mineralization Kinetics

Cumulative N mineralization in different soils after 112 days of incubation at 32°C ranged from 8.2 to 75.6 mg N kg⁻¹ soil. This constituted 2.7 to 8.8% of organic N. The amount of N mineralized was linearly related to soil OC (Figure 1). Figure 1 shows that for each gram of OC per kg soil, approximately 9 mg N was mineralized in 112 days of incubation. The time course of cumulative N mineralized in different soils showed (Figure 2) that mineralization was faster during initial days of incubation followed by a relatively slower rate subsequently. In most of the soils, 50% of the total N mineralization (112 days) had occurred by 28 days of incubation, whereas the remaining 50% occurred in next 84 days. This suggested that the initial rapid

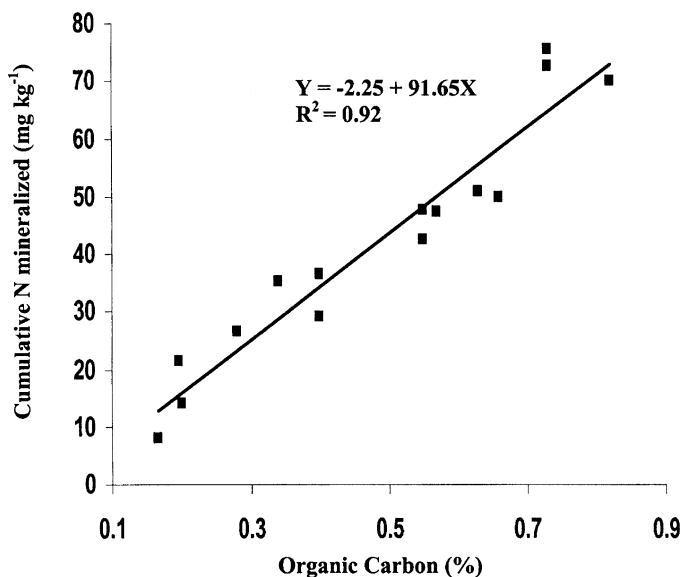


FIGURE 1 Relationship of cumulative N mineralized in 112 days of aerobic incubation at 32°C to soil organic carbon content.

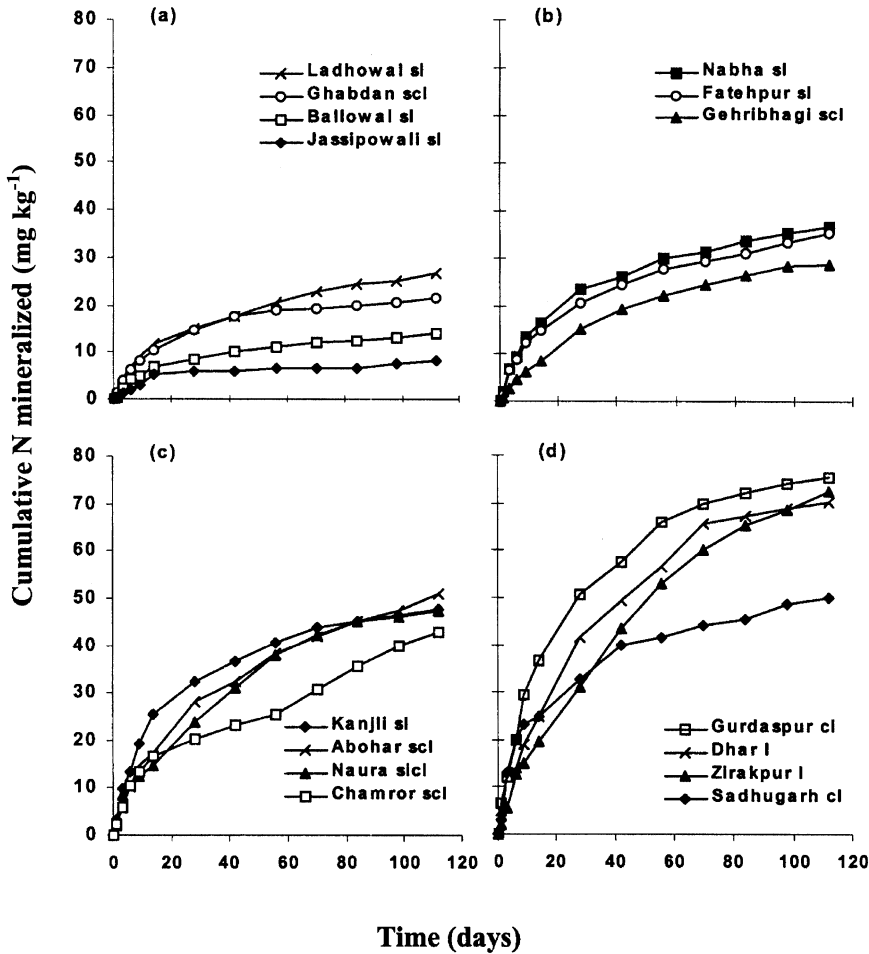


FIGURE 2 Time course of cumulative N mineralized in 15 benchmark soils of Punjab, India, with organic carbon content (a) 0.17 to 0.28%, (b) 0.34 to 0.40%, (c) 0.55 to 0.63%, and (d) 0.66 to 0.82%.

phase of mineralization was from an easily decomposable pool of organic matter whereas the later phase was from a recalcitrant fraction.

Different models of varying complexity (Table 2) were fitted to describe the shape of N mineralization vs. time curve. The parameter estimates for different models are presented in Table 3. The N mineralization potential (N_0) for different soils as estimated from FOSC model ranged from 7.0 to 82.5 mg kg⁻¹ with a mean of 41.6 mg kg⁻¹. The mineralization rate constant, k , ranged from 0.018 to 0.067 day⁻¹ with an average of 0.04 day⁻¹. The average mineralization rate constant for these soils was found to be higher by more than an order of magnitude than that (0.007 day⁻¹ at 35°C) reported by Stanford and Smith (1972) for 39 US soils. Contrarily, the N mineralization potential of these soils was generally lower than those (18–305 mg N kg⁻¹) reported for US soils. This suggests that although the soils in this region have small N mineralization potential, they have high turnover rates.

First-order double compartment (FODC) model could not be fitted to N mineralization in Chamror sandy clay loam (scl) whereas in Jassipowali sandy loam (sl) the model yielded unstable parameter estimates. This was probably due to the

TABLE 3 Kinetic Parameters Estimated for Different Models Fitted to Cumulative N Mineralization vs. Time Data. N_o , N_d , N_r , and N_e mg kg^{-1} and k_d , k_r and K day^{-1}

Soil	FOSC			FODC			FOZO			MFO		
	N_o	k	N_d	k_d	N_r	k_r	N_d	k_d	K	N_o	N_e	K
Jassi Powali	7.0	0.067	— ^a	—	—	—	5.4	0.097	0.020	7.0	−0.2	0.071
Ghabdan	20.3	0.051	11.9	0.088	10.8	0.017	16.1	0.071	0.046	20.5	−0.2	0.046
Ballowal	12.8	0.045	6.4	0.123	14.6	0.007	7.5	0.104	0.059	13.4	1.2	0.034
Ladhowal	25.2	0.037	8.1	0.189	25.1	0.012	12.8	0.108	0.130	27.1	2.8	0.025
Fatehpur	32.9	0.040	11.4	0.156	29.7	0.014	18.9	0.091	0.148	34.6	3.1	0.030
Nabha	34.4	0.044	13.6	0.138	28.0	0.015	21.7	0.087	0.137	35.8	3.2	0.034
Gehri Bhagi	31.2	0.023	14.5	0.037	20.9	0.011	23.9	0.030	0.055	31.6	0.4	0.022
Kanjli	44.9	0.053	20.1	0.141	31.8	0.018	31.4	0.092	0.154	46.3	4.2	0.041
Chamror	41.9	0.024	—	—	—	—	12.2	0.213	0.272	62.1	6.2	0.009
Naura	49.9	0.026	4.5	1.048	50.0	0.019	32.3	0.041	0.148	53.7	3.8	0.012
Abohar	50.1	0.028	12.8	0.126	50.5	0.012	25.0	0.068	0.233	53.0	3.2	0.023
Sadhugarh	45.4	0.065	18.4	0.279	34.9	0.019	29.4	0.145	0.195	47.6	6.9	0.042
Gurdaspur	73.1	0.047	20.7	0.169	58.4	0.025	53.1	0.073	0.216	75.1	5.8	0.038
Zirakpur	82.5	0.018	4.1	0.377	85.5	0.015	48.2	0.030	0.239	86.7	2.4	0.016
Dhar	72.1	0.031	5.7	1.148	70.2	0.024	52.9	0.043	0.171	75.3	4.9	0.025

^aindicates no realistic solution.

shape of N mineralization curve for the two soils. In Naura silty clay loam (sicl) and Dhar loam (l), the rate constants for the easily decomposable fraction was very high as compared to the other soils. In the remaining 11 soils the decomposable organic N fraction (N_d) ranged from 4.1 to 20.7 mg N kg⁻¹ with associated rate constants k_d of 0.04 to 0.377 day⁻¹ (average 0.165 day⁻¹). The recalcitrant organic N fraction (N_r) was larger than the decomposable fraction and ranged from 10.8 to 85.5 mg kg⁻¹ in different soils. The mineralization rate constant, k_r , for the recalcitrant fraction was lower by an order of magnitude (average 0.015 day⁻¹) as compared to that (0.165 day⁻¹) for the decomposable fractions. N mineralization potentials estimated from the FODC model, as sum of $N_d + N_r$, were higher (range 21–89.7 mg kg⁻¹) than those yielded by the FOSC model. The decomposable fraction (dpm) on average had half-life of 5 ± 3 days as compared to 49.5 ± 20 days for the recalcitrant fraction (rpm). The half-lives for the two fractions estimated in the current studies are lower than those reported by Nordmeyer and Richter (1985) for loess and sandy soils from Germany (8–12 days for dpm and 100–140 days for rpm at 35°C). The dpm fraction with small half-life may be considered to contribute toward crop N uptake for a short period during early days of crop growth, whereas the rpm fraction may contribute during the later stages of crop growth for a longer period of time.

The decomposable fraction (N_d) was not related to soil OC content (Figure 3). This is understandable as N_d originates due to residues from the last crop and due to drying and rewetting of the soils prior to incubation. Drying and rewetting the soils causes changes in soluble organic matter. Some of the solubilized organic compounds may come from the microbial biomass, which is killed by drying the soil samples. On rewetting, the dead biomass becomes mineralized rapidly (Nordmeyer & Richter, 1985; Van Gestel et al., 1991). Conversely, the recalcitrant fraction that represents the plant material which accumulates within the soil was positively related to soil OC (Figure 3). The relationship was well described by a power function.

Unlike FODC model, the first-order zero-order (FOZO) model could be fitted precisely to all the soils. The N_d values (5.4 to 53.1 mg kg⁻¹) predicted by the model were quite different from those obtained with FODC model. The first-order decomposition rate constant, k_d , ranged from 0.03 to 0.21 day⁻¹ (average 0.09 day⁻¹)

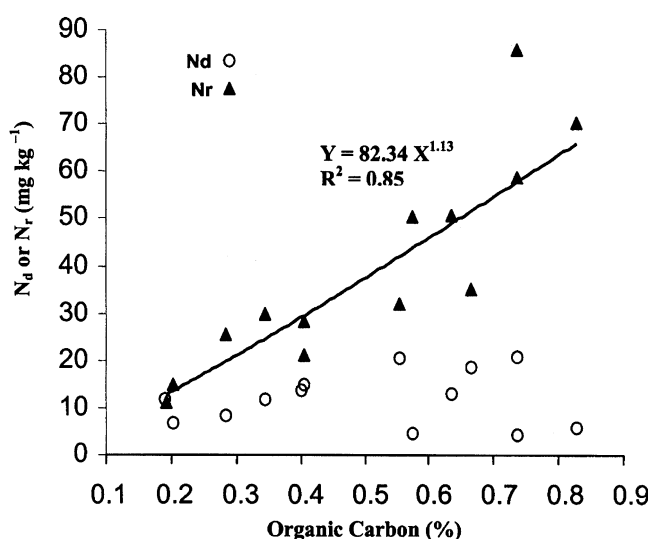


FIGURE 3 Relationship of nitrogen mineralization potential of easily decomposable (N_d) and recalcitrant fraction (N_r) derived by FODC model.

and the zero-order rate constant K , ranged from 0.02 to 0.27 day⁻¹ (average 0.148 day⁻¹) (Table 3).

The modified first-order (MFO) model predicted N_o similar to FOSC model, which ranged from 7.0 to 86.7 mg N kg⁻¹ soil with a mean of 44.7 mg N kg⁻¹ soil. The first-order rate constant, k , varied between 0.012 and 0.071 day⁻¹. The N_e values were found to be ranging from -0.16 to 6.9 mg kg⁻¹ with an average of 3.2 mg N kg⁻¹.

The empirical power function, in most of the soils, accounted for more than 95% variability in the data (Table 4). The "a" values ranged from 0.66 to 7.62 and that of the exponent (b) varied between 0.50 and 0.77 indicating nonlinear shape of the N mineralization curve. Notwithstanding high R^2 values, no physical significance can be attached to the regression coefficients.

Comparison of Models

Typical fit of different models on two soils, viz. Ladhowal sl (OC 0.28% and clay 10%) and Sadhugarh cl (OC 0.66% and clay 35%) are illustrated in Figure 4. The FOSC model systematically deviated from the measured values. The fitted curve underestimated the measured values at the beginning and end of the incubation period and overestimated at intermediate times. These results are similar to those of Bonde and Rosswall (1987) and Seyfried and Rao (1988). This implies that the underlying assumption of the FOSC model, that there is a single distinct homogeneous pool of soil organic N which mineralizes so fast (according to first-order kinetics) that the other pools may be ignored, does not hold. Therefore, the principle applicability of FOSC model is questionable. The seemingly good fit to the FOSC model in some other studies may partly be attributed to the method (linear least squares) of parameter estimation. The linearized form of the model was employed to arrive at the values of N_o giving best linear fit for the regression of $\log(N_o - N_t)$ on t (Stanford & Smith, 1972). With the logarithmic transformation, undue weight is

TABLE 4 Regression Coefficients (a and b) and Coefficient of Determination (R^2) for the Power Function ($N_t = at^b$) Fitted to Cumulative N Mineralization (N_t , mg kg⁻¹) vs. Time (t , days) in Different Soils

Soil name	a*	b*	R^2 *	$R^{2*}(Y, \hat{Y})$
Jassi Powali	0.66	0.57	0.90	0.86
Ghabdan	1.80	0.57	0.93	0.93
Ballawal	0.88	0.63	0.88	0.95
Ladhowal	2.04	0.58	0.95	0.98
Fatehpur	2.44	0.61	0.92	0.97
Nabha	3.03	0.57	0.94	0.96
Gehri Bhagi	0.97	0.77	0.97	0.96
Kanjli	4.91	0.52	0.94	0.95
Chamror	3.13	0.56	0.97	0.98
Naura	3.72	0.56	0.99	0.99
Abohar	2.77	0.65	0.97	0.98
Sadhugarh	5.61	0.50	0.86	0.95
Gurdaspur	7.62	0.52	0.97	0.96
Zirakpur	2.59	0.74	0.98	0.99
Dhar	5.59	0.57	0.98	0.98

*significant at $P = 0.05$.

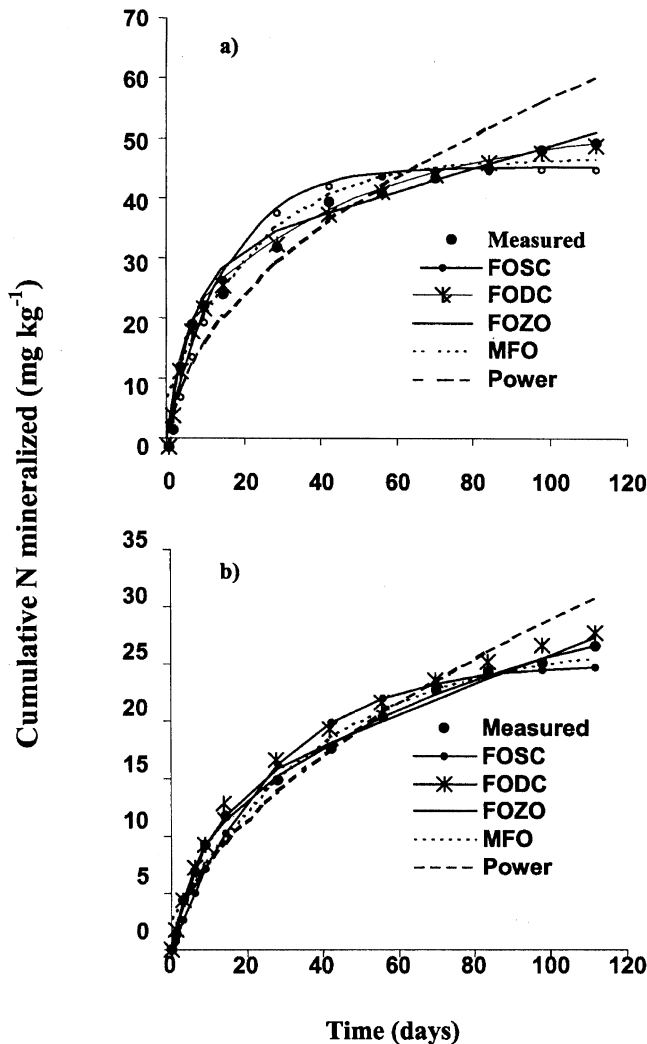


FIGURE 4 Typical fit of different models to cumulative N mineralization data from two soils (a) Ladhawal sl, (b) Sadhugarh cl with widely different OC and clay contents.

given to data from the end of incubation (Talpez et al., 1981) and errors in the data are also log-transformed. This makes it difficult to evaluate precisely the fit of the model to the data.

The FOSC model, irrespective of the soil, invariably yielded highest residuals followed by MFO model (Table 5). In 10 out of the 15 soils, to which FODC model could be fitted, it yielded the minimum residuals. In the remaining five soils, the FOZO model yielded the minimum residuals. This implies that a minimum of two pools of organic matter contribute toward organic N mineralization. A comparison of goodness of fit of different models using *F*-test on their residual mean squares (RMS) showed that FOSC model was significantly ($P=0.05$) inferior to the other models (except Jassipowali sl and Gehri Bhagi scl, where all models were at par). The MFO model generally behaved poorly as compared to FOZO and FODC model, except in Naura sicl, Zirakpur l, and Dhar l, where the model was at par with FOZO and FODC models. Physically, the MFO model may also be interpreted as a

TABLE 5 Residual Mean Squares (RMS) Yielded by Different Kinetic Models Fitted to Cumulative N Mineralization vs. Time Data in Different Soils

Soil	FOSC	FODC	FOZO	MFO
Jassi Powali	0.37a	—	0.27a	0.41a
Ghabdan	0.43b	0.12a	0.11a	0.31b
Ballawal	0.72b	0.08a	0.01a	0.57b
Ladhowal	2.68d	0.14a	0.37b	1.42c
Fatehpur	3.57c	0.39a	0.54a	2.15b
Nabha	3.39c	0.39a	0.56a	2.01b
Gehri Bhagi	0.16a	0.14a	0.13a	0.14a
Kanjli	5.57d	0.57a	1.02a	3.50c
Chamror	15.3c	—	0.93b	6.92b
Naura	4.68c	1.21a	4.71b	1.36a
Abohar	4.25c	0.61a	0.79a	2.34b
Sadhugarh	14.1d	1.98a	3.64b	9.64c
Gurdaspur	9.10c	1.28a	3.25b	4.11b
Zirakpur	3.17b	1.41a	3.04b	1.90a
Dhar	7.68b	2.85a	7.42b	2.93a

For a given soil, RMS values followed by different letters indicate significant difference ($P=0.05$) between the models based on F test on the residuals.

two-fraction model with mineralization potentials of N_e and N_o . But N_e is defined as dead microbial biomass pool created due to air-drying of soils prior to incubation, whereas the dpm fraction in FODC and FOZO models is defined as decomposable plant material. Therefore, N_e is not same as N_d in the FODC and FOZO models.

From the above comparison of models, it is apparent that a minimum of two pools of organic matter may be considered to contribute toward organic N mineralization in these soils. In soils with OC content $\leq 0.55\%$, the FOZO model was generally at par with FODC model. However, in soils with OC content $> 0.55\%$, the FODC model invariably provided the best fit.

Relationship of N Mineralization Potential to Soil Properties

Cumulative N mineralized after 112 days of incubation (N_{112}) at 32°C was significantly ($P=0.05$) correlated to soil OC, organic N, and total N (Table 6). The relationship between N_{112} and soil OC was higher as compared to that with organic N and total N. The N mineralization potential predicted by both FOSC and FODC models was positively and significantly ($P=0.05$) correlated to total N, organic N and OC. Earlier studies also reported high correlations between N_o and organic C (Campbell et al., 1981; Griffin & Laine, 1983) and total N (Marion et al., 1981; Campbell et al., 1981; Griffin & Laine, 1983; Hadas et al., 1986; Campbell et al., 1991). Contrarily, Carter and Macleod (1987) found that N_o was poorly related to OC and organic N in podzols and luvisols of Prince Edward Island.

Regression analysis of N mineralization potential vs. OC and/or clay content showed that OC alone could account for 88% variability in N_o predicted by FOSC model (Equation 6) and 89% variability in $N_d + N_r$ predicted by FODC model (Equation 7):

$$N_o = -3.05 + 94.53 \text{ OC}^{**} \quad R^2 = 0.88^{**}, \quad \text{and} \quad (6)$$

TABLE 6 Correlation of N Mineralization Potentials Derived from FOsc and FODC Models, to Other Soil Properties

Component	N ₁₁₂ ^a	N _o ^a	N _d ^b	N _r ^b	N _d + N _r ^b
N ₁₁₂	—	0.99*	0.09	0.92*	0.98*
OC	0.96*	0.95*	0.10	0.88*	0.94*
Organic N	0.90*	0.90*	−0.09	0.87*	0.88*
Total N	0.89*	0.90*	−0.13	0.88*	0.88*
Mineral N	0.23	0.29	−0.52*	0.39	0.27
Clay	0.24	0.20	0.27	0.07	0.15
Sand	−0.63*	−0.61*	−0.06	−0.52*	−0.56*

^aBased on all the 15 soils.^bBased on 13 soils to which FODC model could be fitted.*Indicates significant at $P=0.05$.

$$N_d + N_r = 3.27 + 95.39 \text{ OC}^{**} \quad R^2 = 0.89^{**}, \quad (7)$$

where * and ** indicate significant at $P=0.05$ and 0.01 , respectively.

Clay content alone was a poor predictor of N_o and $N_d + N_r$. The regression coefficient for clay in both the cases was nonsignificant. Introducing OC and clay together as independent variables in the equations significantly improved the predictability (Equations 8 and 9). For both the models, OC and clay together accounted for more than 91% variability in N mineralization potential of soils.

$$N_o = 5.57 + 101.62 \text{ OC}^{**} - 0.57 \text{ clay} \quad R^2 = 0.91^{**}, \quad \text{and} \quad (8)$$

$$N_d + N_r = 12.87 + 103.29 \text{ OC}^{**} - 0.63 \text{ clay}^* \quad R^2 = 0.93^{**}. \quad (9)$$

To see whether there is an interactive effect of clay and OC, another variable (Clay \times OC) was introduced along with OC and clay as independent variables (Equations 10 and 11):

$$N_o = -26.09 + 165.44 \text{ OC}^{**} + 1.14 \text{ clay} - 3.28 (\text{clay} \times \text{OC})^* \quad R^2 = 0.95^{**}, \quad \text{and} \quad (10)$$

$$N_d + N_r = -7.22 + 143.79 \text{ OC}^{**} + 0.45 \text{ clay} - 2.08 (\text{clay} \times \text{OC})^* \quad R^2 = 0.94^{**}. \quad (11)$$

Though it slightly improved the predictability, the regression coefficient for clay was nonsignificant in both the equations. Therefore, clay as an independent variable was dropped to arrive at the following equations (12 and 13):

$$N_o = -5.34 + 128.16 \text{ OC}^{**} - 1.30 (\text{clay} \times \text{OC})^* \quad R^2 = 0.93^{**}, \quad \text{and} \quad (12)$$

$$N_d + N_r = 0.98 + 129.05 \text{ OC}^{**} - 1.30 (\text{clay} \times \text{OC})^{**} \quad R^2 = 0.94^{**}. \quad (13)$$

The equations show that N mineralization potential is directly dependent upon soil OC content, but mineralization is retarded because of an interaction between OC and clay content. This negative interaction may be ascribed to greater physical

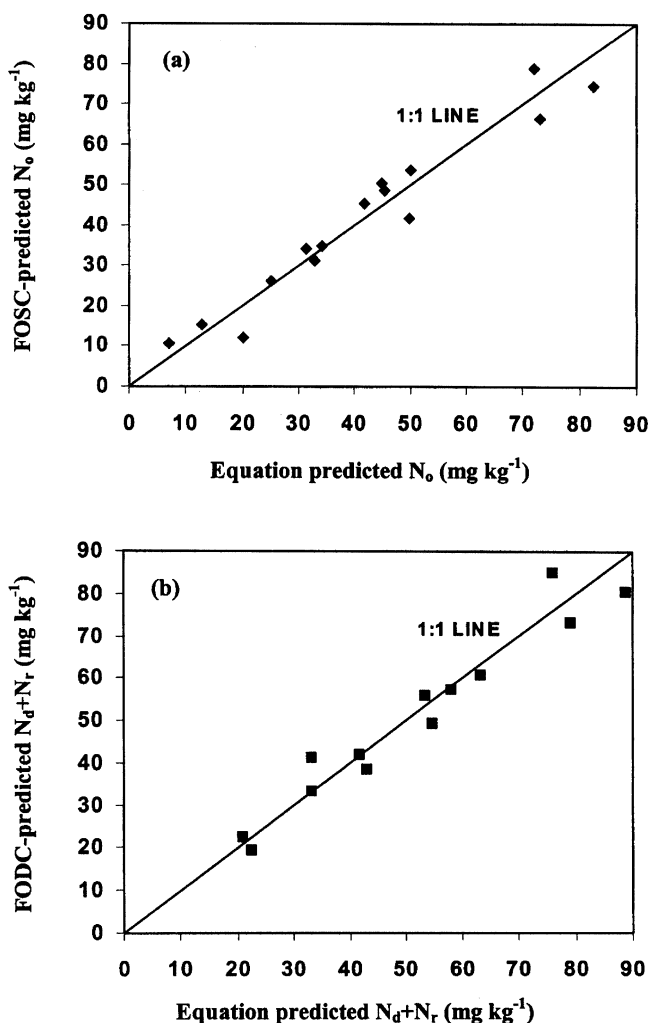


FIGURE 5 Relationship of FOSC and FODC model-predicted N mineralization potentials to Equation 12 and 13 predicted N mineralization potentials, respectively.

protection offered by clays to soil organic matter and microbial biomass (Verberne et al., 1990). Among the mechanisms suggested to explain the phenomenon of physical protection in soil are encrustation by clay particles (Tisdall & Oades, 1982) and entrapment in small pores in aggregates inaccessible to microbes (Elliott & Coleman, 1988).

The internal consistency of Equations 12 and 13 was checked by plotting N_o and $N_d + N_r$ computed from these equations against the corresponding parameter predicted by FOSC and FODC models. It is apparent (Figure 5) that there was a close match between the two. Therefore, either Equation 12 or 13 can be used to predict N mineralization potential of the experimental soils. The equations are convenient to use as the only input required is soil OC and clay content.

In conclusion, it may be stated that, though the soils of this semiarid region of NW India are low in organic C, these have high turnover rate. Under disturbed conditions, N mineralization kinetics of these soils could be best described by two compartment models (FODC and FOZO). Clay and soil OC strongly influence N

mineralization potential of soils from this semiarid region and the two together could be used to predict N mineralization potential of these soils. These conclusions are similar to those of Benbi and Richter (2002). Based on a comparative evaluation of a number of kinetic models on published data from different regions of the world, they (Benbi & Richter, 2002) concluded that a minimum of two organic N fractions are considered essential to significantly contribute toward N mineralization.

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