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# Unravelling the Release Kinetics of Exchangeable Magnesium in Acid Soil of Nilgiris

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**Abstract:** Magnesium deficiency is a pervasive and recurrent factor that significantly restricts crop production, primarily attributable to the low levels of exchangeable magnesium (ex-Mg) present in acidic soil conditions. This deficiency exerts a pronounced negative influence on the sustainability and progress of agricultural development. Hence the current study aspired at modeling the kinetics of Exchangeable Magnesium release from 3 fertilizer sources i.e., Epsom salt ($MgSO_4{\cdot}7H_2O$), Magnesite ($MgCO_3$) and Dolomite [$CaMg(CO_3)_2$] in the acidic soil of the Nilgiris district in Tamil Nadu, India. Four mathematical models were verified—Power function, parabolic diffusion, Simple-Elovich, and first-order to explain cumulative $Mg^{2+}$ release. Power function was noticed to be an outstanding empirical equation finely fitted to the experimental data. The intensity, as well as the modality of the release pattern, was predicted by the numerical parameters. The power function as well as Parabolic Diffusion portrayed the $Mg^{2+}$ release kinetics best as verified by the maximum correlation coefficients ($r^2$). The parabolic diffusion model also designated the data as suitable, signifying diffusion-controlled exchange. From the derived dissolution rates, it was conceivable to agree Epsom salt ($MgSO_4{\cdot}7H_2O$) from which the release was faster than the other two magnesium sources. In conclusion, these outcomes provided an insight into the temporal dynamics of magnesium availability in acidic soil, highlighting the importance of understanding its release kinetics for sustainable agriculture development. The findings contribute to the broader knowledge of magnesium management strategies, aiding in the development of targeted interventions to alleviate magnesium deficiency and optimize crop productivity in acidic soil environments.

**Keywords:** magnesium; acidic soil; $Mg^{2+}$ release; kinetic models; power function

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## 1. Introduction

Magnesium is a crucial element for crops as well as human beings, the deficiency of which alters carbohydrate partitioning and photosynthesis in crops [1], moderates sustainable agricultural production as well as development, which produces long-term negative influences on animals as well as human well-being [2,3]. Noticeable Magnesium deficiency symptoms often arise in crops, exclusively at their critical developmental stage by means of quick carbohydrate accumulation, grown up in acidic soils broadly disseminated around the domain [1,4]. Comestible agricultural foodstuffs are the foremost source of Magnesium nutrition for animals as well as humans. Hence, sustaining the magnesium contents of agricultural produces within a comparatively sufficient range is the most significant.

Soil acidity is another imperative component responsible for the reduced productivity of crops [5,6], strongly concomitant with the deficiency of phosphorus, potassium, magnesium, calcium, as well as zinc, whereas the toxicity of aluminium along with manganese [7,8] antagonizes the magnesium [9]. As $Mg^{2+}$ ion exhibits a highly mobile nature, hence, it becomes susceptible to leaching due to intense rainfall [10–12], specifically in the case of acidic soils, declining nutrient use efficiency along with crop yield.

Soil pH directly influences the liberation of Magnesium from clay minerals at the same time equally on Mg uptake in plants. Chan et al. [13] and Hailes et al. [14] revealed that Mg is exchangeable at a soil pH below 6.0, and non-exchangeable when soil pH is elevated above 6.5. Likewise, Sumner et al. [15] stated that when the pH of Ultisols enhanced from 5.5 to 7.5, soil exchangeable Mg plummeted more than 50%. Even though higher soluble Mg concentrations in soil solution are quite high plant uptake of Mg can be hindered by a surplus content of other cations i.e., $H^+$ [16]. Higher levels of exchangeable aluminium, are liberated in acid soils (pH below 5). Moreover, at the rhizosphere region, the H+ ions exist alternative to basic cations in soil solution [16]. In this situation, the decline in available Mg for plants at low soil pH is a corollary of the boosting incompetence to sustain adequate pH, therefore electrochemical gradient occurs across the plasma membrane of root cells [12,17]. Soil exchangeable Mg content may upsurge at low pH; in spite of this, the ascendency of $H^+$ at the rhizosphere region may impede the uptake of Mg, triggering Mg deficiency plus hindering yield along with agricultural products quality [18].

Up to date, the maximum emphasis has been provided to the nitrogenous, phosphatic, and potassic fertilizers compared to Magnesium to achieve maximum yield of crop [19]. Intensive cropping as well as harvest in soils that are not being replaced with Magnesium fertilizers causes in reduction of native Mg from the soil along with extensive deficiency of Mg. Currently, the deficiency of Mg has grown into a pervasive problem, harshly plummeting photosynthetic rates of crops specifically cultivated in acidic soils [20–24]. Theoretically, deficiency of Mg occurs for two reasons, i.e., (a) absolute deficiency; (b) cationic competition. Absolute deficiency can be an outcome of (i) the source rocks with low Mg contents [25], (ii) Mg losses from the soil i.e., by mobilization followed by consecutive leaching [10,11] (iii) long-term unbalanced crop fertilization practice ignoring Mg depletion of soils due to removal by the crop [26].

The form of nutrient soils has been considered an essential feature always, swaying the magnesium availability predominantly, meanwhile there is an immense discrepancy in solubility in water between the numerous magnesium sources [27]. The four best equations indicating magnesium release are the parabolic diffusion equation based on kinetic chemistry and that the constants of this equation are used to explain the liberated ions in the soil and the Power function model is experimental. The finest kinetic equations can be determined to describe the release and adsorption of the element by comparing the values of the correlation coefficient ($r^2$) as a measure of the preference between the equations. The equivalent Parabolic diffusion equation states that the driving force of the propagation process arises from the difference between the liberated element as well as its concentration in the outer solution. However, the release of absorbed quantity is directly proportional to time and is raised to a certain square [28].

Until now, no effort done to scientifically scrutinize the influences of Mg fertilizers on their release pattern in acid soils. In Nilgiris, Tamil Nadu, India the soils are highly acidic, $H^+$ saturation is excessive, as well as more prone to leaching of Mg because of heavy rainfall. Hence, it is crucial to provide Mg fertilizer to such soils for the maintenance of soil fertility as well as productivity. To address all these issues, the current study endeavored to postulate more acumens into the mechanism of release pattern of exchangeable Mg in response to several magnesium fertilizer sources and to refine and use various kinetic models to explain Mg release in acid soils of Nilgiris.

## 2. Materials and Methods

### 2.1. Climate and Location

In the current experiment, the soil was collected from a farmer's field (11°24′08.0″ N, 76°39′50.6″ E) in Nilgiris, Tamil Nadu belonged to the soil taxonomy of Ultic Tropudalf. The soil of this study was typically of low Mg status. The location comes under a subtropical climate receiving a mean annual rainfall of 1390 mm besides exhibiting a mean annual temperature of 15 °C.

### 2.2. Soil Collection and Analysis

The soil was collected from the surface (0–15 cm), packed in polythene covers, and carried to the laboratory. The soil was air-dried for one week at room temperature, ground then passed through a 2-mm sieve before the arrangement of microcosms. The physico-chemical properties of soil are furnished in Table 1. The incubation study was laid down at the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, in a completely randomized design (CRD) with two replications. A control microcosm that had received no Mg fertilizers was taken as control. Each microcosm contained 100 g of soil. Five doses of Mg were inoculated in each soil as $MgSO_4{\cdot}7H_2O$, $MgCO_3$, and $CaMg(CO_3)_2$ at 10, 20, 30, 40, and 50 kg Mg ha$^{-1}$ soil total of 16 treatments. Water holding capacity was estimated, as summarized by [29]. Double distilled water was used to saturate the soil to field capacity based on weight loss then reinstated to field capacity by the addition of required double distilled water at 2 days intervals. On 5, 10, 20, 30, 40, 50, and 60 days after incubation destructive sampling was carried out, dried, homogenized, then taken for analysis of basic soil properties and available nutrients as per standard procedures. The control along with fifteen treatments was established in replicates ($n = 2$). The incubation was conducted in an incubator at 25 °C with 60% humidity in the dark.

**Table 1.** Initial physico-chemical properties of the experimental soil.

| Soil Properties | Soil |
|---|---|
| Texture | Sandy loam |
| Bulk density (Mg m$^{-3}$) | 1.32 |
| pH | 5.24 |
| EC (dS m$^{-1}$) | 0.29 |
| OC (%) | 6.36 |
| Total N (%) | 0.17 |
| Total P (%) | 0.16 |
| Total K (%) | 0.25 |
| Total Mg (mg kg $^{-1}$) | 1912 |
| Avail. N (kg ha $^{-1}$) | 282 |
| Avail. P (kg ha $^{-1}$) | 55 |
| Avail. K (kg ha $^{-1}$) | 442 |
| Exch. Ca (mg kg$^{-1}$) | 18 |
| Exch. Mg (mg kg$^{-1}$) | 10.5 |
| Available S (mg kg$^{-1}$) | 13.7 |
| DTPA Extractable Fe (mg kg$^{-1}$) | 100 |
| DTPA Extractable Mn (mg kg$^{-1}$) | 2.56 |
| DTPA Extractable Zn (mg kg$^{-1}$) | 2.26 |
| DTPA Extractable Cu (mg kg$^{-1}$) | 2.49 |

### 2.3. Soil Chemical Parameters

Soil texture was analyzed by the international pipette method then sand, silt, and clay content was estimated as per the standard procedure of [30], and soil textural class was determined using the soil textural class triangle given by United State Department of

Agriculture (USDA) [31]. The pre-incubation soil pH was estimated electrometrically in 1:2.5 soil: water suspension as elucidated by [32]. The Cation Exchange Capacity (CEC) along with exchangeable bases viz., $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, and $K^{+}$ were estimated by 1 N $NH_4$-acetate (pH 7) saturation method. Exchangeable $Ca^{2+}$ and $Mg^{2+}$ were analysed by versenate method [33], and exchangeable $K^{+}$ and $Na^{+}$ using a flame photometer [32]. The wet oxidation method by Walkely and Black was used to estimate organic carbon [34]. Kjeldahl digestion-distillation method was used to estimate total N as explained by [35]. Available P was estimated by the Bray-1 method [36] and then analyzed spectrophotometrically at 660 nm. Plant available micronutrient cations (Fe, Cu, Zn, and Mn) from the soil were analyzed by the 0.5M DTPA reagent [37]. The cumulative Mg released by the different sources into the soil solution was plotted against incubation time intervals for the experimental soil.

### 2.4. Kinetic Models

Four kinetic models were draw on to fit the Mg release patterns as illustrated by [38–40].

$$\text{First order: } \ln(q0 - qt) = a - bt \tag{1}$$

$$\text{Parabolic diffusion: } q = a + bt^{1/2} \tag{2}$$

$$\text{Power function: } \ln q = \ln a + b \ln t \tag{3}$$

$$\text{Power function: } \ln q = \ln a + b \ln t \tag{4}$$

where q is the amount of $Mg^{2+}$ released, qt is the cumulative $Mg^{2+}$ released at time t, t, is the time of release, q0 is the maximum $Mg^{2+}$ released, whereas a and b are constants. Constant b is the key term of these equations, which depicts the rate of release of exchangeable Mg. All these mathematical equations were verified by least square regression analysis to conclude which model best describes exchangeable Mg release from soils. Coefficients of determination ($r^2$) were obtained by least square regression of measured vs. predicted values. First-order, parabolic diffusion as well as Elovich models were also verified, as the data did not fit and hence are not explained in detail.

The empirical equation for power function model is furnished by

$$q = a\, t^{\,b} \tag{5}$$

where q is the concentration (mmol $L^{-1}$) of each element in the solution at time t, where a (mmol $L^{-1}$ $days^{-n}$) and b (dimensionless) are constants. Equation (4) has been generally used earlier for explaining the kinetics of plant nutrient release from natural materials [41,42], and also for kinetics of minerals dissolution [43,44]. As compared to the other kinetic models such for example the pseudo-second-order equation, power function has the practical benefit [45], where it can be utilized for modelling non-equilibrium experimental conditions. The more the values of a and b, the more is the element release rate with time. Besides, b provides evidence on how the release rate differs during the incubation period; as time goes on, the rate of release of each element declines ($b < 1$, remains constant ($b = 1$) or raises ($b > 1$), respectively.

The Elovich equation is depicted by

$$q = 1/a \ln(a\, b) + 1/a \ln(t) \tag{6}$$

where a (L $mmol^{-1}$) and b (mmol $L^{-1}$ $days^{-1}$) are constants. The Elovich equation, initially developed for gas adsorption [46], has also been furnished for modelling minerals dissolution. Few cases are the phosphate rock dissolution in acidic sandy soils [47] as well as of zinc silicate in ammoniacal solution [48].

### *2.5. Statistical Analysis*

Linear forms of the four kinetic equations were fitted to the experimental data, individually for each source with all the levels of concentration applied. The coefficient of determination ($r^2$) values and Mg release rate parameters were consequently obtained from fitted equations as follows: the "a" and "b" from the simple Elovich equation [49], "a" and "b" from power function model [50] were computed using OriginPro 8.5.0. The obtained data were subjected to factorial completely randomized design in SPSS 16.0 software for Windows (SPSS Inc., Chicago, IL, USA) in one-way analysis of variance (ANOVA) for studied soil. The mean was compared using Tukey's Honestly significant difference (HST) at $p \leq 0.05$.

## 3. Results

The soil was acidic, low in EC, whereas the organic matter content was high. The texture of the soil was found to be Sandy loam (66.02% sand, 17.18 silt, and 16.08 clay), and bulk density was 1.32 Mg m$^{-3}$. The CEC value was 18.6 cmol (p$^+$) kg$^{-1}$. Exchangeable Mg$^{2+}$ was 10.5 mg kg$^{-1}$. Selected chemical and physical properties of the experimental soil are displayed in Table 1.

### *Kinetics of Magnesium Release*

The cumulative Mg$^{2+}$ release pattern was practically parallel with magnesium sulphate, magnesium carbonate and dolomite, however magnesium sulphate released more Mg$^{2+}$ compared the other two sources. Cumulative exchangeable Mg released after 60 days in magnesium sulphate, magnesium carbonate and dolomite varied from 74.97 to 239.37 mg kg$^{-1}$, 75.02 to 133.0 mg kg$^{-1}$ and 75.5 to 127.7 mg kg$^{-1}$, respectively (Figure 1a–c). With increasing levels of Mg, an increasing trend was noticed in the release of exchangeable magnesium in all the tested sources. Among the various sources tested, the cumulative Mg release was found to be higher in $MgSO_4 \cdot 7H_2O$ @50 kg Mg ha$^{-1}$ as compared to control. The release of magnesium followed the order $MgSO_4 \cdot 7H_2O$ @ 50 kg Mg ha$^{-1}$ > $MgCO_3$ @ 50 Kg Mg ha$^{-1}$ > $CaMg(CO_3)_2$ @ 50 Kg Mg ha$^{-1}$ (Table 2).

The constant 'b' denotes the slope which could be considered as an index of Mg$^{2+}$ release rates. The parameter 'b' (Table 3) was less than 1 in all soils, represented the decrease in exchangeable Mg$^{2+}$ release rates with time. The Mg$^{2+}$ release rate explains the cumulative Mg release over a period of time. In case of power function model, the release rates ranged from 0.757 to 0.972 in Magnesium sulphate treated soil, from 0.757 to 0.889 mg kg$^{-1}$ in magnesium carbonate treated soil and from 0.759 to 0.907 in dolomite treated soil. The rate of release decreased with increasing levels of Mg in the case of $MgSO_4 \cdot 7H_2O$ and was found to be maximum @ 10 kg Mg ha$^{-1}$ as compared to higher levels. The release rate followed a different trend in the case of $MgCO_3$ @ 30 kg Mg ha$^{-1}$. The rate of release increased with increasing levels of Mg in the case of dolomite and was found to be maximum @ 50 kg Mg ha$^{-1}$ as compared to the control.

**Table 2.** Cumulative Mg released (kg ha$^{-1}$) from soil treated with Magnesium sulphate, Magnesium carbonate, and Dolomite.

| **Levels of Mg(kg ha$^{-1}$)** | **Cumulative Mg Released after 60 Days from Different Sources** | | |
|---|---|---|---|
| | **Epsom Salt ($MgSO_4 \cdot 7H_2O$) (mg kg$^{-1}$)** | **Magnesite($MgCO_3$) (mg kg$^{-1}$)** | **Dolomite [$CaMg(CO_3)_2$] (mg kg$^{-1}$)** |
| 0 | 74.97 | 75.02 | 75.5 |
| 10 | 168.19 | 108.4 | 101.1 |
| 20 | 181.77 | 113.7 | 107.8 |
| 30 | 198.2 | 120 | 113 |
| 40 | 221.27 | 126.3 | 119.4 |
| 50 | 239.37 $^a$ | 133 $^b$ | 127.7 $^b$ |

Means with the different letters are significantly different at $p = 0.05$ by Tukey's (HSD) test.

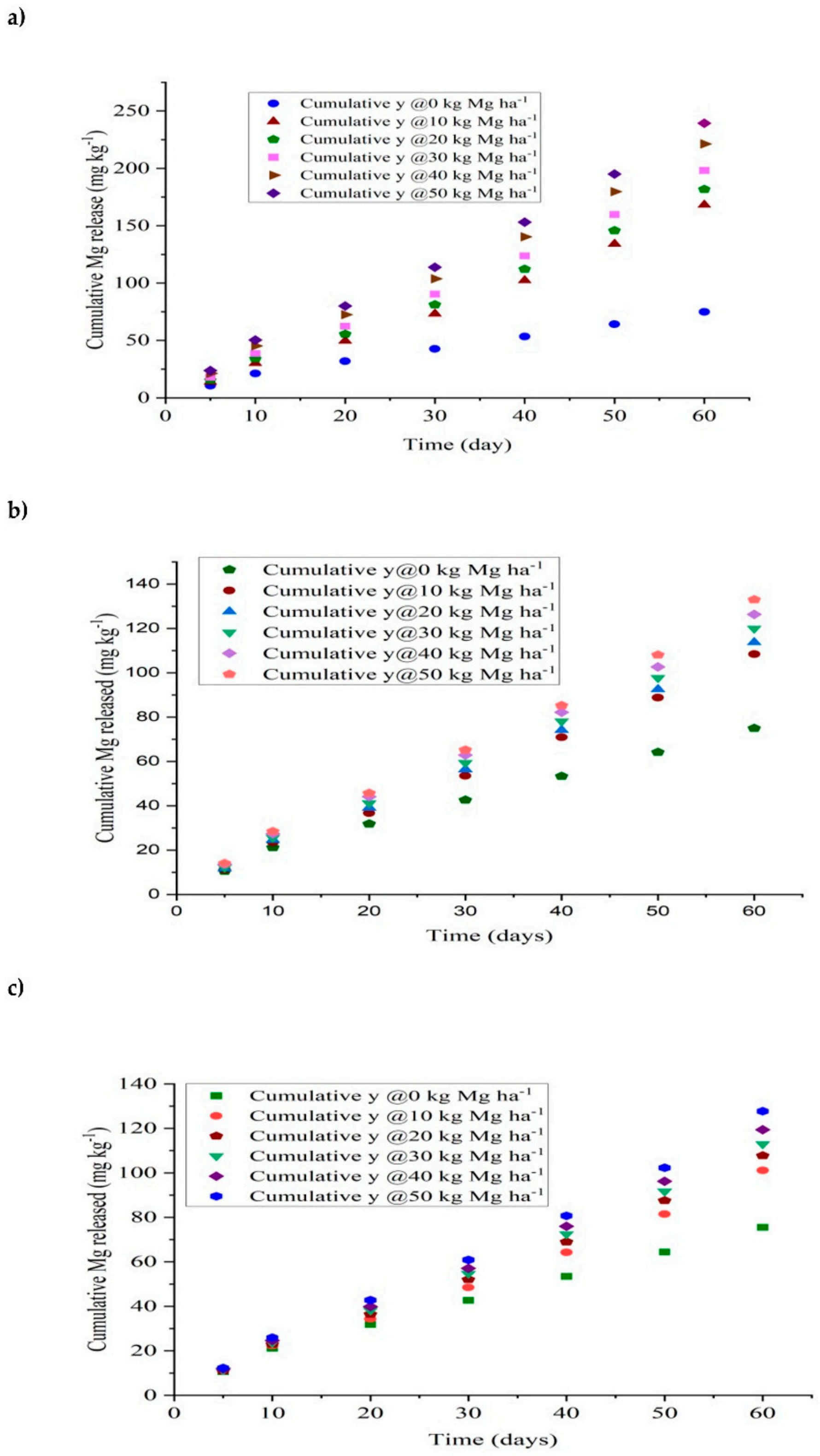

**Figure 1.** The cumulative amount of exchangeable Mg release with time, (**a**) Epsom salt; (**b**) Magnesite; and (**c**) Dolomite solution.

**Table 3.** Parameters of models used to elucidate release kinetics of exchangeable $Mg^{2+}$ from Magnesium sulphate, Magnesium carbonate, and Dolomite in studied acid soil.

| **Sources** | **Levels of Mg (kg ha$^{-1}$)** | **First Order** | | **Elovich** | | **Power Function** | | **Parabolic Diffusion** | |
|---|---|---|---|---|---|---|---|---|---|
| | | **a (mg kg$^{-1}$)** | **b (mg kg$^{-1}$ d$^{-1}$)** | **a (mg kg$^{-1}$)** | **b (mg kg$^{-1}$ d$^{-1}$)** | **a (mg kg$^{-1}$)** | **b (mg kg$^{-1}$ d$^{-1}$)** | **a (mg kg$^{-1}$)** | **b (mg kg$^{-1}$ d$^{-1}$)** |
| $MgSO_4{\cdot}7H_2O$ | 0 | 4.901 | −0.063 | −34.871 | 24.674 | 1.204 | 0.757 | −16.420 | 11.341 |
| | 10 | 6.040 | −0.071 | −98.950 | 57.460 | 1.070 | 0.972 | −58.970 | 26.980 |
| | 20 | 6.120 | −0.072 | −105.410 | 61.990 | 1.227 | 0.954 | −61.980 | 29.060 |
| | 30 | 6.220 | −0.073 | −113.000 | 67.350 | 1.409 | 0.932 | −65.630 | 31.530 |
| | 40 | 6.397 | −0.074 | −123.630 | 74.950 | 1.620 | 0.908 | −70.540 | 35.010 |
| | 50 | 6.424 | −0.075 | −132.090 | 80.910 | 1.757 | 0.895 | −74.560 | 37.750 |
| $MgCO_3$ | 0 | 4.903 | −0.063 | −34.920 | 24.690 | 1.203 | 0.757 | −16.460 | 11.350 |
| | 10 | 5.451 | −0.066 | −59.280 | 36.710 | 1.024 | 0.883 | −32.990 | 17.100 |
| | 20 | 5.505 | −0.067 | −61.940 | 38.410 | 1.069 | 0.883 | −34.380 | 17.880 |
| | 30 | 5.572 | −0.067 | −65.700 | 40.630 | 1.110 | 0.889 | −36.540 | 18.910 |
| | 40 | 5.626 | −0.068 | −67.750 | 42.420 | 1.235 | 0.867 | −37.300 | 19.740 |
| | 50 | 5.696 | −0.068 | −71.740 | 44.630 | 1.260 | 0.872 | −39.880 | 20.800 |
| $CaMg(CO_3)_2$ | 0 | 4.913 | −0.063 | −35.218 | 24.828 | 1.200 | 0.759 | −16.690 | 11.420 |
| | 10 | 5.362 | −0.065 | −53.644 | 33.550 | 1.026 | 0.859 | −29.810 | 15.660 |
| | 20 | 5.447 | −0.066 | −58.668 | 36.256 | 1.012 | 0.882 | −32.830 | 16.910 |
| | 30 | 5.508 | −0.067 | −62.226 | 38.201 | 1.011 | 0.895 | −34.960 | 17.810 |
| | 40 | 5.577 | −0.067 | −65.740 | 40.237 | 1.055 | 0.896 | −37.140 | 18.770 |
| | 50 | 5.660 | −0.068 | −70.725 | 43.068 | 1.077 | 0.907 | −40.060 | 20.090 |

The curve fit between all the models and experimental data are displayed by the coefficients of determination ($r^2$) as indicated in Table 4. As compared to all other models, the power function model showed a maximum value of $r^2$. The minimum value of $r^2$ was found in the case of the first order (release of the nutrient is independent of the concentration of sources) which means the release of Mg does not fit the first order equation which indicates the dependency on the concentration of sources and the Figures 2a, 3a and 4a revealed that the points deviate from the first order curve fitting line. The $r^2$ value is observed to be the highest in the case of dolomite among all the sources. With the increase in the levels of Mg, there is an increase in the $r^2$ value in all the sources (Figures 2d, 3d and 4d). These results explained the perfect fitting of points at all the intervals to the curve fitting line in the case of the power function equation.

**Table 4.** Coefficient of determination ($r^2$) of different kinetic models for exchangeable Mg release in experimental soil.

| **Sources** | **Conc. of Levels (kg ha$^{-1}$)** | **First Order** | **Elovich** | **Power Function** | **Parabollic Diffusion** |
|---|---|---|---|---|---|
| | | $r^2$ | $r^2$ | $r^2$ | $r^2$ |
| $MgSO_4{\cdot}7H_2O$ | 0 | 0.791 | 0.932 | 0.994 | 0.988 |
| | 10 | 0.671 | 0.857 | 0.993 | 0.949 |
| | 20 | 0.671 | 0.865 | 0.993 | 0.953 |
| | 30 | 0.670 | 0.869 | 0.994 | 0.956 |
| | 40 | 0.669 | 0.877 | 0.994 | 0.960 |
| | 50 | 0.668 | 0.881 | 0.994 | 0.963 |
| $MgCO_3$ | 0 | 0.790 | 0.932 | 0.994 | 0.988 |
| | 10 | 0.721 | 0.889 | 0.994 | 0.968 |
| | 20 | 0.714 | 0.892 | 0.995 | 0.969 |
| | 30 | 0.711 | 0.892 | 0.995 | 0.970 |
| | 40 | 0.705 | 0.892 | 0.996 | 0.970 |
| | 50 | 0.700 | 0.887 | 0.995 | 0.966 |
| $CaMg(CO_3)_2$ | 0 | 0.787 | 0.931 | 0.994 | 0.988 |
| | 10 | 0.710 | 0.879 | 0.993 | 0.961 |
| | 20 | 0.713 | 0.883 | 0.995 | 0.964 |
| | 30 | 0.710 | 0.886 | 0.996 | 0.966 |
| | 40 | 0.701 | 0.881 | 0.996 | 0.963 |
| | 50 | 0.694 | 0.882 | 0.996 | 0.963 |

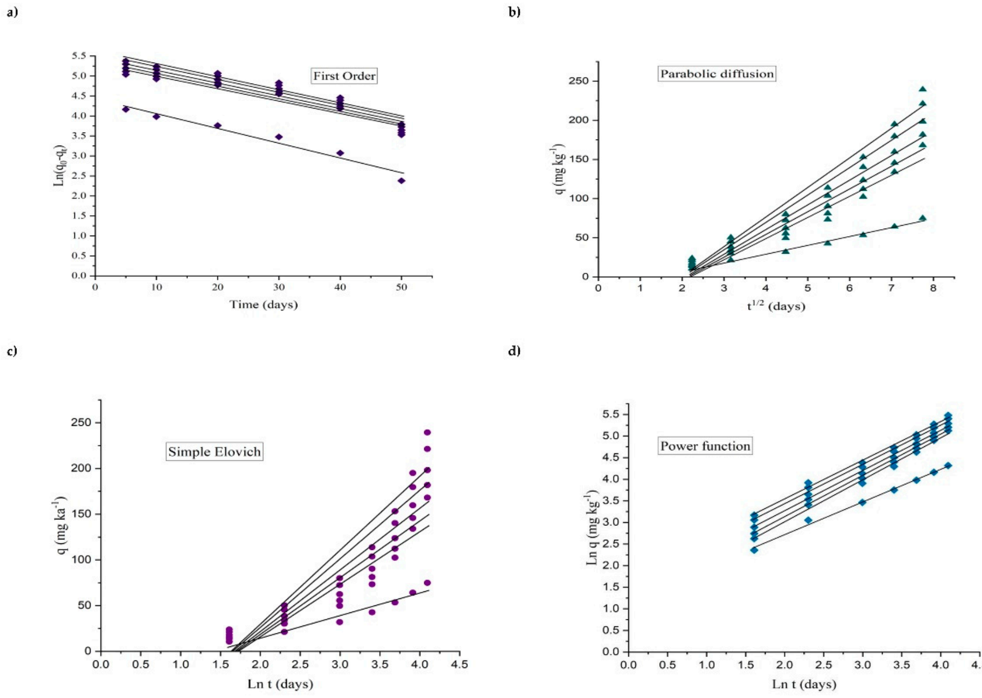

**Figure 2.** Relationships between observed and predicted exchangeable Mg release kinetics by Epsom salt ($MgSO_4 \cdot 7H_2O$) at different concentrations as described by mathematical models.

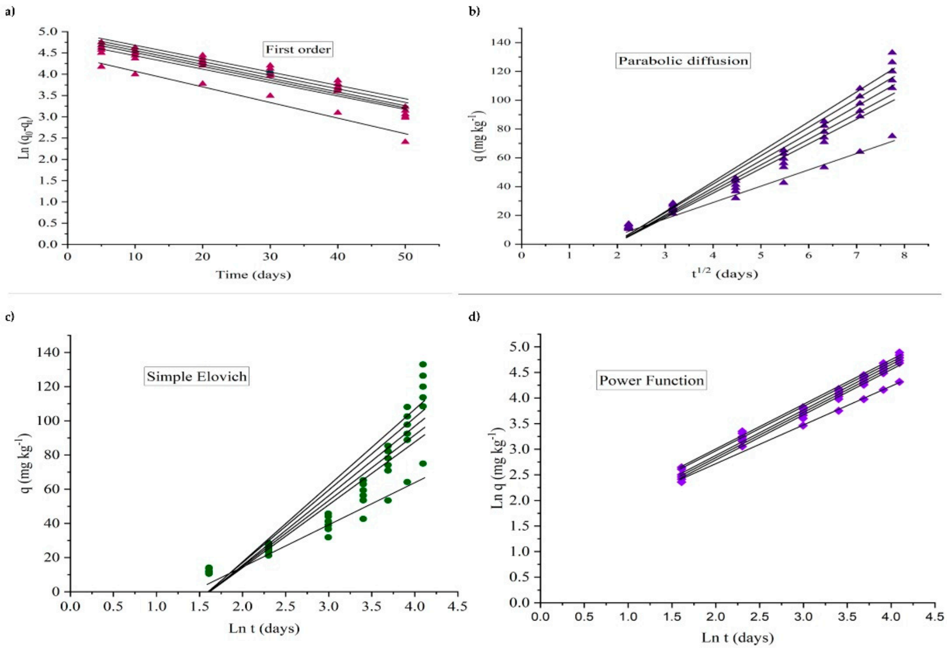

**Figure 3.** Relationships between observed and predicted exchangeable Mg release kinetics by Magnesite ($MgCO_3$) at different concentrations as described by mathematical models.

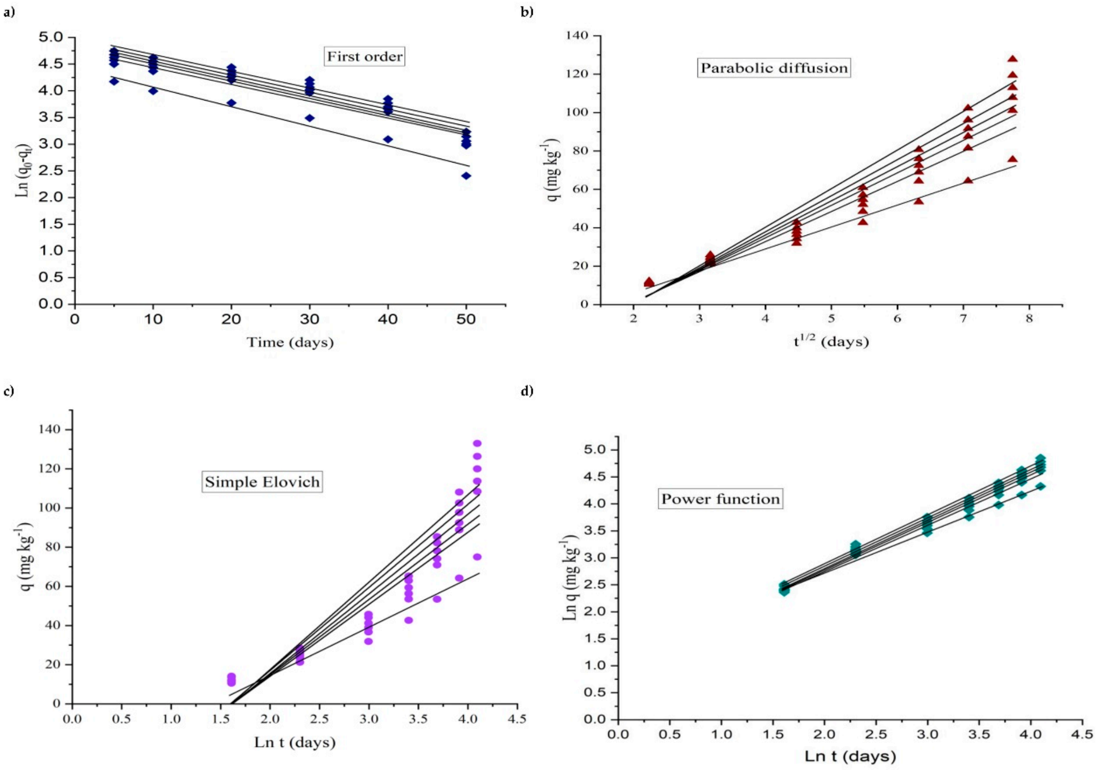

**Figure 4.** Relationships between observed and predicted exchangeable Mg release kinetics by Dolomite [$CaMg(CO_3)_2$] at different concentrations as described by mathematical models.

## 4. Discussion

*Depiction of Magnesium Release by Kinetic Models*

Plots of cumulative exchangeable $Mg^{2+}$ release in Magnesium sulphate, Magnesium carbonate and Dolomite are shown in Figure 1a–c. All the plots of the Mg release data for three sources with 6 levels with different equations are shown in Figures 2–4. Figure 1a show the magnesium release curves of the studied soil samples, where the amount of release increases the reaction by increasing the concentrations of levels of source in the experimental soil. It is shown by the behavior of these curves that there is a general tendency to increase the amount of free magnesium with the increase in the concentration of source ($MgSO_4 \cdot 7H_2O$) until 40 days; this increase gradually decreases over time in all soil samples during 40 to 60 days. But in the case of Magnesite ($MgCO_3$) and Dolomite ($CaMg(CO_3)_2$), the increase is gradual and the rate of increase increased over time from 0 to 60 days.

When we follow the magnesium release processes in the soils above, two stages of emancipation can be distinguished, which appear clearly in soil samples with the low magnesium content. In the early stages, the release of magnesium takes the form of a highly inclined curve over short periods of time (the release of a massively magnified magnesium mass over a small time period). In the second stage, there is a decrease in the slope of the magnesium release curves to follow the shape of the straight line and is almost parallel to the *y*-axis. This stage represents the release of magnesium that is difficult to release; these results agree with [51]. Sequential addition of more concentrations of fertilizer source to the soil headed to a rise in the amount of released magnesium by constantly changing the movement of dissolved materials due to ion exchange and release processes of magnesium-bearing fertilizer that get between the liquid as well as solid phases of the soil. The amount of magnesium released by fertilizers surpassed the rest of the long interaction periods may be due to weak ion bonding on the surface of colloids, which is a very high proportion of ion exchange capacity, and higher solubility that leads to easy liberation of Exchangeable Mg. It is observed that the greater the reaction time, the less release amount depends on the reaction products during the process of emancipation of the ion, but the liberation does not reach the fixed state of emancipation since the release of the magnesium, in this case, represents the relatively easy magnesium release in the soil solution along with the magnesium adsorbed on the location. The slow-release magnesium fertilizers, are associated with specialized adsorption sites and less solubility, resulting in a slow release from the clay to the soil solution [52]. There is a similarity in the behavior of the cumulative magnesium release curves of all levels in general. However, the total cumulative magnesium release from the soil differed according to magnesium levels for a particular source of Mg.

In order to know the best equation elucidating the release of magnesium in the study soil and to detect the mechanics of this liberation, applied standards of kinetics, which represent the best means to calculate and emancipate the emancipation of ions from the soil and the purpose of the application of these criteria is the motor to obtain the coefficient of the speed of the release of ions in the concept of kinetic chemistry, hence the interactions within the soil depending on the time factor, where four equations are used: First Order, Parabolic diffusion, Power function, and Elovich. For the purpose of determining the best kinetic equation, the highest value of the $r^2$ is taken, as displayed in Table 4. The study findings showed that the maximum value of $r^2$ (0.994) was found in the Power function equation compared to all other equations. Figure 1a–c showed the relationship between the cumulative and time-release amount of magnesium for the incubated soil sample treated with various magnesium fertilizers, and the statistical plot by Origin 8.5 notes that most points are located on the extension of the straight line. The highest value of the magnesium release speed coefficient is 0.972 shown in Table 4 that treated with magnesium sulfate at 20 kg ha$^{-1}$ according to the Power function equation, whereas the lowest value of 0.84 when treated with magnesium sulfate at 10 kg ha$^{-1}$ according to the power function equation. From this, we concluded that enhancing the concentration of the fertilizer sources leads headed for a rise in the speed of the release coefficient of magnesium and may be due to the role of electrolytic concentration of fast release and slow-release fertilizers by electrical conductivity. The differences in $Mg^{2+}$ release at different intervals between Magnesium sulphate ($MgSO_4{\cdot}7H_2O$), Magnesium carbonate ($MgCO_3$) and Dolomite [$CaMg(CO_3)_2$] can be recognized as alterations in their nature of reaction with soil. On the surface of a mineral $Mg^{2+}$ ions can exchange H+ ions, because of their greater size as well as hydration energy, they cannot easily exchange interlayer $Mg^{2+}$. A substantial increase by $MgCO_3$ was only marked during the last sampling interval (60 days after application). However, even 60 days after application, both $MgCO_3$ and $CaMg(CO_3)_2$ fertilizers had a lesser influence on rising the Mg availability than $MgSO_4{\cdot}7H_2O$. This suggested the slow-release nature of these latter two fertilizers [53]. Though $MgSO_4{\cdot}7H_2O$ enhanced the Mg availability of the soil instantly after treatment, the available Mg content show a steady as well as continual emancipation of magnesium from this source until 60 days after treatment. These interpretations are in accordance with the outcomes of other workers [54,55]. Conquering an explanation of a power function equation for exchangeable $Mg^{2+}$ release from soils was previously explained by some researchers [28,42,56]. The fitting of the data to the power function equation showed a straight line (Figures 2–4). A successful explanation of $Mg^{2+}$ release by the power function model was also conveyed by Abed et al. [57]. A successful explanation of $Mg^{2+}$ release by the parabolic model was formerly narrated by Abed et al. [57].

## 5. Conclusions

The results indicated that soil treated with high magnesium solubility could release magnesium higher than low solubility. Mathematical scrutiny of magnesium release data revealed that the power function, Elovich, parabolic diffusion, and first-order equations each explained Magnesium release kinetics. The fitting of the data to the power function model signposted that it was considered by an initial faster rate followed by a slow rate in all soils. Data derived from mathematical models will provide a way to describe the release kinetics and estimate the magnesium-delivering power of soil. The kinetic behavior of the magnesium ion release among all the equations showed the highest coefficient of determination in power function. The study recommends further research on the kinetic behavior of magnesium release from the soil and consideration of the behavior and properties of magnesium in the management of acid soils of Nilgiris with low levels of magnesium when using magnesium fertilizers. It also requires observing the behavior of magnesium when reclaiming acidic soil to avoid reaching the limits that exhibit plant deficiency.

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