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Urea dissolution time in water and efficiency of foliar application in oat crops

**C.L.Peter, J.A.G. da Silva, I.R. Carvalho, D.A. Magano,
G.M. Conceição, O. Alessi, J.A. da Rosa, C.M. Babeski, P. Diel,
M.V.R. Sarturi, L.B. Heusner and N.G. Zardin**

Regional University of the Northwest of the State of Rio Grande do Sul, Ijuí, RS, Brazil.

Corresponding author: I.R. Carvalho
E-mail: carvalho.irc@gmail.com

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ABSTRACT. Nitrogen via solid urea is easily lost by volatilization and leaching. This element, due to its easy absorption and translocation, shows the possibility of foliar supply. Knowledge of the dynamics of urea dissolved in water and foliar spraying on oats can improve use efficiency. The bjective of this study was to assess the urea dlution time under non-linearity of air temperature, and validate the technology of foliar application of urea dissolved in water in oat crops, considering different water volumes and urea (N) rates and the oat grain yield in different crop systems. The urea dissolution was carried out in laboratory, using a randomized block experimental design with four replications, in a 4×7 factorial arrangement, consisted of 4 water volumes (100, 200, 300, and 400 L ha^{-1}) and 7 urea rates (0, 44, 88, 132, 164, 176, 220, and 264 kg ha^{-1}). After determining the appropriate water volume for urea dissolution (300 L ha^{-1}), a field experiment was carried out for foliar application, using a randomized block design with four replications, in a 2×7 factorial arrangement, consisted of application of two urea sources (solid and dissolved) and seven N rates (0, 20, 40, 60, 80, 100, and 120 kg ha^{-1}). The water volume of 300 L ha^{-1} dissolves the rates of urea, resulting in the expected oat grain yield for the nitrogen rates. The use of high rates increases the urea dissolution time; high air temperature facilitates this dissolution. The use of the technology of urea dissolved in water for foliar application results in similar yields to those using applications to the soil, making it an alternative for supplying N to oat crop systems.

Key words: *Avena sativa* L.; Nitrogen; Air Temperature; Sustainability; Yield; Agenda 2030

INTRODUCTION

White oat (*Avena sativa* L.) is a cereal grown worldwide that has been highlighted due to its benefits to human health; it is recognized as a functional food of high nutritional quality (Basso et al., 2022; Dornelles et al., 2023). The growth of oat crops requires the use nitrogen (N) fertilizers. N acts directly on metabolic processes of the plant and is decisive for defining the yield (Mantai et al., 2021a; Ju et al., 2022). The main N source used in oat cultivation is urea, which is a white, crystalline solid compound of high solubility in water (Reginatto et al., 2021; Oliveira et al., 2022). Its advantages include high N concentration (45%), low transport cost, compatibility with various fertilizers and pesticides, easy handling, and quick availability to plants (Henrichsen et al., 2022; Oliveira et al., 2023). Broadcast application is commonly used for applying urea to the soil; the N released is absorbed by the roots of the plants (Polese et al., 2018; Santos et al., 2020).

The recommended N application time for oat crops is between 25 to 45 days after emergence; however, meteorological conditions is not always favorable for applying N in this period (Kraisig et al., 2020; Reginatto et al., 2021). High temperatures and low soil moisture due to absence of rainfall in periods prior to N application cause losses by volatilization, while excessive rainfall, even in a short period of time right after its application cause losses by leaching (Reginatto et al., 2021; Trautmann et al., 2022). The ease of loss of N by volatilization by urea, causes the release of ammonia, contributing to the pollution of the atmosphere and aggravation of greenhouse effect (Yamamoto et al., 2016; Henrichsen et al., 2022). The leaching of N causes the release of nitrate, which that leads to contamination of surface and underground water sources, a threat to public health due to continuous consumption of contaminated water, which increases the risks of manifestation of certain types of diseases (Martínez-Dalmau et al., 2021; Basso et al., 2022). Therefore, advances are needed in the development of strategies that promote better use of N in oats, improving the N efficiency to reduce environmental and public health impacts (Mantai et al., 2021b; Trautmann et al., 2021).

N is a mobile element, easily absorbed and translocated in plant tissues; studies have shown the potential of foliar N application (Fan et al., 2020; Henrichsen et al., 2023). The use of urea dissolved in water is a technology that facilitates the absorption of N with low environmental losses (Azeem et al., 2014; Henrichsen et al., 2022). The water used for the urea dissolution and nutrient vehicle can favor the cooling of the leaves and promote the opening of stomata, facilitating the entry of N (Mortate et al., 2018; Henrichsen et al., 2023). The amount and nature of the solute, volume and temperature of the solvent, and air temperature directly affect the dissolution capacity. Temperature is the only physical factor capable of modifying the solubility of a solvent in relation to the solute (Shnidman and Sunier, 1931; Atahar, et al., 2019). Preliminar studies on foliar application of urea dissolved in water showed its effectiveness in wheat (Khan et al., 2009) and corn (Petean et al., 2019); however, they did not clearly determine the urea dissolution time, the water volume used, and the effects of temperature on the dissolution capacity.

The objective of this study was to assess the urea dissolution time under non-linearity of air temperature, and validate the technology of foliar application of urea dissolved in water in oat crops, considering different water volumes and urea (N) rates and the oat grain yield in different crop systems.

MATERIAL AND METHODS

The study of urea dissolution in water was conducted in 2019, at the Plant Production Laboratory of the Regional University of Northwestern Rio Grande do Sul (Unijuí), Brazil. Four water volumes were used as solvent (100, 200, 300, and 400 L ha^{-1}), considering volumes that have been used in most field fertilizer applications by farmers, and seven urea rates (0, 44, 88, 132, 176, 220 and 264 kg ha^{-1}), considering the range of N (nitrogen) rates used for oat crops when applying urea (45% N) (0, 20, 40, 60, 80, 100 and 120 kg ha^{-1}).

The study of urea dissolution time in water and validation in the experimental field was carried out by calculating volumes and rates for experimental units of 6 m^2. Thus, the volumes of 100, 200, 300 and 400 L ha^{-1} were represented by the volumes of 60, 120, 180 and 240 mL for the area of 6 m^2, respectively, which were placed in two-liter bottles. The urea rates of 0, 44, 88, 132, 164, 176, 220 and 264 kg ha^{-1} were determined for these volumes, considering the application area of 6 m^2; thus, 0, 26, 53, 80, 107, 133 and 160 g were used, respectively. A randomized block experimental design with four replications was used, in a 4×7 factorial arrangement, consisted of 4 water volumes and 7 urea rates, resulting in a total of 112 bottles for the analysis of the urea dissolution time. Potable tap water was used as solvent; the water physical, chemical, and microbiological characteristics is shown in Table 1.

Table 1. Water physical, chemical and microbiological characteristics used to dissolve urea.

Parameter	Unit	Result	Method	** Reference value	LQ/range
Physical and chemical parameters					
Residual Chlorine	mg/L	< LQ	Standard 4500-CI G	MVA 0.2 - 5.0	0.10
Fluoride	mg/L	<LQ	Standard 4500-F- D	MVA 1.5	0.55
pH*	-	7.45	Standard 4500- H+ B	MVA 6.0-9.5	1-14
Turbidity	NTU	0.85	Standard 2130 B	MVA 5.0	0.10
Microbiological parameters					
Total coliforms	MLN/100 mL	Absence	Standard 9221 E	Absence	1.10
TC	MLN/100 mL	Absence	Standard 9221 E	-	1.10
THBC	CFU/mL	9.00	Standard 9215 B	MVA 500	1.00

*: Parameter(s) recognized by the Meteorological Network RS by NBR ISO IEC 17025 Standard; Methodology: Standard Methods for Examination of Water and Wastewater, 22ed; **: Reference values, Consolidation Ordinance no. 5 of 2017 of the Brazilian Ministry of Health, attachment XX. TC: Thermotolerant coliforms; THBC: Total Heterotrophic Bacterial Count; LQ: limit of quantification; MVA: maximum value allowed; MLN: most likely number; CFU: colony forming unit; NTU: Nephelometric Turbidity Unit. Source: Analytical Center UNIJUÍ (2019).

The urea rates dissolved in water were placed into the bottles, which were shaken for one minute and then left on a table to visually quantify the complete urea dissolution time, with the aid of a digital stopwatch. The study that involved the analysis of urea dissolution was carried out considering 4 different experiments in time, making it possible to involve different conditions of air temperature, for analysis of the effect of the non-linearity of temperature on the dissolution process. These experiments to analyze the effect of temperature took place in the characteristic months of the oat growing season, using a digital thermometer during dissolution. The maximum time of one hour was defined for the dissolution for the highest urea rates, as more concentrated solutions may not completely dissolve, leaving solids at the bottom of the container. It was defined considering an easy preparation and fast possibility of application by the farmer, without making the process disadvantageous.

The field experiment was carried out in the 2019 and 2020 agricultural years, in Augusto Pestana, RS, Brazil (28°26'30"S and 54°00'58"W), municipality located in the region largest oat production in the country. The soil of the experimental area was classified as a Typic Hapludox (Latossolo Vermelho Distroferrico tipico) (Santos et al., 2018). The region presents a Cfa climate, with hot summer without a dry season, according to the Köppen classification. Soil analysis was carried out 20 days before sowing to determine physical and chemical characteristics, as shown in Table 2.

Table 2. Chemical composition of the soil of the experimental area.

Crop systems	**Clay (%)**	**OM (%)**	**pH (H_2O)**	**P (mg dm^{-3})**	**K (mg dm^{-3})**	**AL (cmol$_c$ dm^{-3})**	**Ca (cmol$_c$ dm^{-3})**	**Mg (cmol$_c$ dm^{-3})**
Maize-oat	52	2.9	6.2	40.8	239.7	0	6.5	2.5
Soybean-oat	54	3.2	6.5	26.9	179.5	0	6.3	2.7

OM= organic matter; P= phosphorus; K= potassium; Al= aluminum; Ca= calcium; Mg= magnesium.

After defining the most suitable water volume for dissolving the urea, two field experiments were carried out to validate the technology, one for each crop system (soybean-oat and maize-oat). A randomized block design with four replications was used in each system, in a 2×7 factorial, consisted of applications of two urea sources (solid and dissolved) and seven N rates (0, 20, 40, 60, 80, 100 and 120 kg ha^{-1}), totaling 112 plots for both systems. Seeds of the oat cultivar Brisasul, recommended for cultivation in southern Brazil, were sown in the experimental plots using a seeder-fertilizer, with 5 6-meter rows spaced 0.20 m apart, to form experimental units of 6 m^2. The population density used was 400 viable seeds m^{-2}. This cultivar is characterized by early cycle, low height, and great yield potential. During the sowing, 45 kg ha^{-1} of P_2O_5 and 60 kg ha^{-1} of K_2O were applied. The control of diseases and weeds were carried out by applying the fungicide tebuconazole (Folicur® CE), at the rate of 0.75 L ha^{-1} and the herbicide metsulfuron-methyl (Ally®), at the rate of 4 g ha^{-1}, and manual weeding when necessary. The treatments (N rates from solid and dissolved urea sources) were applied at the oat phenological stage V4, when the oat plants presented four expanded leaves. Solid urea was applied manually and the urea dissolved in water was applied using a knapsack sprayer, with a maximum pressure of 25 psi and flow rate of 1.0 L min^{-1}, through cone jet nozzles. It is noteworthy that the applications were carried out in full sun in the early afternoon, at a time of day with higher temperatures, above 25º C.

When the oat grains had moisture around 15%, grain yield was estimated by harvesting the three central rows of each plot, using a harvester, to validate the results in the field experiment. The grains were taken to the laboratory for cleaning and correction of moisture to 13% and then weighed to obtain the yield, which was converted into kg ha^{-1}.

In the laboratory experiments, when the assumptions of homogeneity and normality were met by the Bartlett's test, analysis of variance was carried out for urea rates and water volumes within each urea dissolution time, up to one hour (data not shown). The means were then compared by the Scott and Knott test at 5% probability level, comparing urea rates within each water volume condition. Regression analysis was performed, considering linear ($y = b_0 + b_ix$) and quadratic ($y = b_0 + b_1x + b_2x^2$) models for describing the results of the urea dissolution time as a function of urea rates in each water volume. Multiple linear regression analysis was used to simulate the urea dissolution time and define the adequate water volume for urea dissolution, based on the controlled effects of rates and water volume under non-linearity of air temperature.

The multiple linear regression model used was based on the following general equation:

$$y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n + \varepsilon \qquad \text{(Eq. 1)}$$

Described in matrix form as:

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \cdots \\ Y_n \end{bmatrix}; X = \begin{bmatrix} 1 & X_{11} & X_{21} & \dots & X_{p1} \\ 1 & X_{12} & X_{22} & \dots & X_{p2} \\ \dots & \dots & \dots & \dots & \dots \\ 1 & X_{1n} & X_{2n} & \dots & X_{pn} \end{bmatrix}; \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \cdots \\ \beta_p \end{bmatrix} \ e \ \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdots \\ \varepsilon_n \end{bmatrix} \qquad \text{(Eq. 2)}$$

The matrices enabled to obtain the regression coefficients:

$$\hat{\beta} = (X'X)^{-1}X'Y \qquad \text{(Eq. 3)}$$

The variance of these coefficients was obtained by the covariance matrix of the vector of regression coefficients:

$$C\hat{o}v(\hat{\beta}) = (X'X)^{-1}\hat{\sigma}^2 \ \text{ e } \ \hat{\sigma}^2 = \frac{(Y - X\hat{\beta})(Y - X\hat{\beta})}{n-p-1} \qquad \text{(Eq. 4)}$$

where n is the number of equations and p the number of parameters. The hypothesis test verified was: $\beta_i = 0$ vs H$_a$: $\beta_i \neq 0$ expressed by:

$$t = \frac{\hat{\beta}_i - \beta_i}{\sqrt{\hat{V}(\hat{\beta}_i)}} \qquad \text{(Eq. 5)}$$

In the multiple regression simulation, the independent variables used in the model were: water volume, air temperature, and urea rates with the range of data from data obtained from different experiments carried out in the laboratory.

The field experiments for validation of the technology of urea dissolved in water generated grain yield data that were subjected to analysis of variance to detect the main effects and interactions between N sources and rates in each agricultural year and crop system. Regression analysis was performed to estimate the maximum technical efficiency (MTE = – [(b_1)/(2b_2)]) of N use on grain yield and define the optimal rate that maximizes yield. The N rates that results in the maximum technical efficiency were used in the simulation of oat grain yield. The Genes program was used for all statistical analyses.

RESULTS AND DISCUSSION

The dissolution times of the urea rates in the different water volumes, considering the maximum analysis time of 60 minutes is shown in Table 3. Complete urea dissolution was found for the water volume of 100 L up to 132 kg; for water volume of 200 L up to the rate of 176 kg; for the water volume of 300 L up to 220 kg; and for for water volume of 400 L up to 264 kg, over the time of 60 minutes.

Table 3. Time of dissolution of urea (45% N) rates in different water volumes.

Volume	**Experiment**	**Air**	**Urea rates (kg ha^{-1})**						
(L ha^{-1})	**(n)**	**Temperature (°C)**	**0**	**44**	**88**	**132**	**176**	**220**	**264**
			Urea dissolution time (minutes)						
100	1	22.6	0	10	54	60	-	-	-
	2	20.2	0	13	60	60	-	-	-
	3	20.2	0	13	60	60	-	-	-
	4	10.6	0	15	60	60	-	-	-
	mean	18.4	0	13	59	60	-	-	-
200	1	22.6	0	4	18	54	60	-	-
	2	20.2	0	5	24	60	60	-	-
	3	20.2	0	5	25	60	60	-	-
	4	10.6	0	7	34	60	60	-	-
	mean	18.4	0	5	25	59	60	-	-
300	1	22.6	0	3	9	23	40	60	-
	2	20.2	0	4	15	36	48	60	-
	3	20.2	0	4	15	38	49	60	-
	4	10.6	0	6	19	49	59	60	-
	mean	18.4	0	4	15	37	49	60	-
400	1	22.6	0	1	3	13	20	41	60
	2	20.2	0	2	4	18	24	52	52
	3	20.2	0	2	6	20	27	56	60
	4	10.6	0	4	13	28	55	60	60
	mean	18.4	0	2	7	20	32	52	58

Urea (45% nitrogen). Urea rates/ nitrogen rates = 0/0, 44/20, 88/40, 132/60, 176/80, 220/100, 264/120 kg ha^{-1}

The results showed that increases in water volume facilitates the dissolution of the highest rates of urea. In addition, the dissolution time increased as the urea rates were increased, regardless of the water volume. The results also show the effect of air temperature on the urea dissolution process (Table 4); for example, in the volume of 300 L with the urea rate of 132 kg ha^{-1}, the reduction in air temperature tended to increase the dissolution time, a condition also observed in the other water volumes.

The water volume of 300 L ha^{-1} was considered as the most suitable for field application, since it can dissolve up to 220 kg ha^{-1} of urea in up to 60 minutes. In years favorable to oat crops in Brazil, the maximum biological efficiency of N use is obtained with application of approximately 100 kg ha^{-1} of N (220 kg ha^{-1} of urea) (Mantai et al., 2015; Kraisig et al., 2020). However, this rate has not been recommended, as N favors growth and biomass production, causing lodging, which makes harvesting difficult and reducing grain yield and quality (Marolli et al., 2018; Marolli et al., 2021). Another important aspect is the need to use less water in fertilizer applications, reducing operational time and downtime to fill the spray tanks and saving water (Bárta et al., 2021; Copetti et al., 2022).

According to the regression analysis, the urea dissolution time up to one hour fitted to a linear model, in all analyzed volumes (Table 4). Each kilogram of urea added increased the dissolution time in the water volumes of 100, 200, 300, and 400 L by 0.47, 0.39, 0.29, and 0.24 minutes, respectively.

Table 4. Regression analysis of urea (45% N) dissolution time in water volumes as a function of urea rates.

Volume ($L\ ha^{-1}$)	**Urea Rate ($kg\ ha^{-1}$)**	**N Rate ($kg\ ha^{-1}$)**	**UDT (minutes)**	**Equation** $UDT = a + bx$	**R^2**
100	0	0	0 c	$-1.05 + 0.47^{*}x$	88
	44	20	13 b		
	88	40	59 a		
	132	60	60 a		
200	0	0	0 d	$-4.85 + 0.39^{*}x$	92
	44	20	5 c		
	88	40	25 b		
	132	60	59 a		
	176	80	60 a		
300	0	0	0 e	$-5.21 + 0.29^{*}x$	97
	44	20	4 e		
	88	40	15 d		
	132	60	37 c		
	176	80	49 b		
	220	100	60 a		
400	0	0	0 d	$-7.71 + 0.24^{*}x$	94
	44	20	2 d		
	88	40	7 d		
	132	60	20 c		
	176	80	32 b		
	220	100	52 a		
	264	120	58 a		

UDT= urea dissolution time; R^2= coefficient of determination; * significant at 5% probability by f-test; Means followed by the same letter are not different from each other by the Scott and Knott test at 5% probability level.

Considering the multiple linear regression model, where water volume and urea rate are controlled variables and air temperature is an uncontrolled variable, the adequate adjustment of the coefficients showed satisfactory results in the analyzed scenarios (Table 5).

In the simulation, the air temperature of 18.4º C was used with a rate of 132 kg of urea in different water volumes. The urea rate used is equivalent to a N rate of 60 kg ha^{-1} (Silva et al., 2016), which is a rate that guarantees high yields with economic efficiency, regardless of the agricultural year. Therefore, using the water volume of 300 L, air temperature of 18.4 °C, and urea rate of 132 kg ha^{-1}, the simulation by the proposed model shows a urea dissolution time of 36 minutes, whereas the observed result was 37 minutes, denoting the proximity of the results obtained (Table 5).

Table 5. Multiple linear regression of urea dissolution time (UDT) involving water volume, air temperature, and urea rate.

Variables	**Scope of work**	**Multiple linear regression** $\mathbf{UDT} = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n + \varepsilon$
Water volume (V, L ha^{-1})	[100 - 400]	
Air temperature (T, °C)	[10.6 - 22.6]	$26.02 - 0.45T + 0.34UR - 0.09V$
Urea rate (UR, kg ha^{-1})	[0 - 132]	

Variables	**Value**	**UDTo (minutes)**	**UDTs (minutes)**
Water volume (L ha^{-1})	100	60	54
Temperature (T, °C)	18.4		
Urea rate (UR, kg ha^{-1})	132		
Water volume (L ha^{-1})	200	59	45
Temperature (T, °C)	18.4		
Urea rate (UR, kg ha^{-1})	132		
Water volume (L ha^{-1})	300	37	36
Temperature (T, °C)	18.4		
Urea rate (UR, kg ha^{-1})	132		
Water volume (L ha^{-1})	400	20	27
Temperature (T, °C)	18.4		
Urea rate (UR, kg ha^{-1})	132		

UDTo= observed urea dissolution time; UDTs= simulated urea dissolution time.

Enthalpy is the thermal energy involved in a chemical reaction or process. There are five types of enthalpy that can be calculated: formation, combustion, binding, neutralization, and dissolution. In this context, urea has been widely used in laboratory experiments involving measurements of enthalpy of dissolution due to the low toxicity (House & House, 2017). A solution is formed by the homogeneous mixture of a solute (substance to be dissolved) in a solvent (substance responsible for dissolution) (Catiavala et al., 2023). The study of urea solubility is important to assess the feasibility of its application and interactions between the solute and aqueous solutions (Costa et al., 2015). Mafy et al. (2015) evaluated the self-aggregation and interaction of urea and water and found greater ease of dissolution when increasing the temperature. Atahar et al. (2019) found that air temperature and urea concentration change the dissolution time, the dissolution capacity increases as the temperature and water volume is increased.

After defining the appropriate water volume for application (300 L ha^{-1}), tests were carried out to measure the application time with different urea rates on the 6 m^2 plots in the field. The results of this study are shown in Table 6.

However, changing the urea rate from 0 to 264 kg ha^{-1} changed the application time, based on the sprayer specifications for the 6 m^2 plots, from 15.38 to 29.73 seconds, respectively.

The analysis of variance of data from the study under field conditions showed that the N sources (solid urea and dissolved urea) did not alter the oat grain yield, the difference was only due to the urea rates, regardless of the succession system or agricultural year (Table 7). The absence of source versus rate interaction indicates that the definition of the urea rate is not dependent on the source used. Therefore, urea dissolved in water for foliar absorption in oat crops shows similar results to the urea applied to the soil for root absorption. This result increases the expectations of further improving the N absorption capacity of plants when applying it to the leaves and not to the soil; however, this application involves complex reactions between N and the plant chemical, physical, and microbiological composition.

Table 6. Time of application of rates of urea dissolved in water in the experimental plots.

N rate (kg ha^{-1})	Urea rate (kg ha^{-1})	Urea rate (g 6 m^{-2})	Volume water (mL 6 m^{-2})	Solid mass volume (mL 6 m^{-2})	Spray volume (mL 6 m^{-2})	Application time (s 6 m^{-2})
0	0	0.00	180	0	180	15.38
20	44	26.66	180	20.19	200.19	17.95
40	88	53.33	180	40.40	220.40	19.31
60	132	80.00	180	60.60	240.60	21.08
80	176	106.66	180	80.80	260.80	23.94
100	220	133.33	180	101.00	281.00	26.49
120	264	160.00	180	121.21	301.21	29.73

s = unit of time in seconds; 6 m^{-2} = experimental unit area; volume of solid mass obtained through the urea density (1.32 g cm^{-3}); spray volume = sum of the volume of solid mass and water volume. The volume of water in ml 6 m^{-2} represents the volume of 300 L ha^{-1} of the solvent.

Table 7. Analysis of variance of main effects and interaction of N sources and rates on oat grain yield in different crop systems.

Source of variation	DF	Ssoybean-oat system		Maize-oat system	
		MS_{2019}	MS_{2020}	MS_{2019}	MS_{2020}
Block	3	37503	119382	25210	13044
Source (S)	1	5540	1370	153092	1273
Rate (D)	6	99750*	462165*	703855*	440183*
FXD	6	3963	4334	16745	8910
Error	39	39707	18635	37436	25540
Total	55	-	-	-	-
Mean		1729	1493	1500	1323
CV(%)		11.52	9.14	12.89	12.07

DF = degrees of freedom; MS =mean square; CV = coefficient of variation; * = significant at 5% probability level by the F test.

The mean oat grain yields under the different N rates and sources enabled to develop an equation for estimating the N rate of maximum technical efficiency, regardless of the source used (Table 8). The data fitted to a quadratic model, regardless of the crop system and agricultural year, with a significant angular parameter. The solid and dissolved urea sources resulted in similar mean grain yields, regardless of the crop system. In the soybean-oat system, in 2019, the maximum technical efficiency found was 72 kg ha^{-1} for a grain yield of 1836 kg ha^{-1}. In 2020, the maximum technical efficiency found was 88 kg ha^{-1} for a grain yield of 1660 kg ha^{-1}.

Higher N use efficiency was found in the maize-oat system, verified, mainly in 2019. It is explained by the characteristics of this system, with a previous crop species that does not perform biological N fixation and has higher C/N ratio, making biological degradation difficult due to the high content of lignin in the tissues. Although it is a more restrictive N-residual environment, the maximum N technical efficiency was approximately 90 kg ha^{-1}.

Table 8. Regression analysis for estimating the maximum technical efficiency of N rates to simulate oat grain yields in different years and crop systems.

Source	**N rates (kg ha^{-1})**							**Equation**	**R^2**	**MTE**	**GY$_{MTE}$**
	0	**20**	**40**	**60**	**80**	**100**	**120**				
Soybean-oat system											
2019											
SU	1556	1682	1779	1839	1857	1810	1654	$1523 + 8.67x - 0.06^{*}x^2$	96	72	1836
DU	1524	1631	1746	1773	1890	1768	1706				
2020											
SU	1031	1342	1445	1634	1702	1696	1637	$1048+14.00x-0.08^{*}x^2$	99	88	1660
DU	1062	1265	1501	1609	1691	1644	1647				
Maize-oat system											
2019											
SU	907	1224	1368	1600	1862	1638	1536	$961+17.05x-0.09^{*}x^2$	95	95	1769
DU	1053	1364	1412	1663	1808	1834	1733				
2020											
SU	906	1122	1348	1474	1563	1543	1340	$883+14.81x-0.08^{*}x^2$	97	93	1568
DU	888	1162	1303	1349	1558	1540	1429				

SU = solid urea; DU = dissolved urea; R^2 = coefficient of determination; * = significant at 5% probability by the t-test; MTE = maximum technical efficiency; GY$_{MTE}$ = estimated grain yields by rate by maximum technical efficiency.

Foliar application of fertilizers has some benefits, it provides nutrients to plants at times the soil conditions limit the uptake by roots (Niu et al., 2021). It consists of application of nutrients by spraying the solution on plants to be absorbed by leaves and stems. The quicker improvement of nutritional deficiencies compared to soil application is among its advantages (Ferrari et al., 2021). Studies have reported the efficiency of N foliar application in different cultures. Bernis and Viana (2015) evaluated the effect of foliar N application at different phenological stages of soybean and found that its application on reproductive stages shows the best yield results. Bazzo et al. (2020) evaluated the quality of wheat seeds subjected to soil N fertilization combined with N supplementation by foliar application and found a positive effect of this supplementation on the physiological quality of the seeds. Nóbrega et al. (2023) evaluated basil crops under foliar N fertilization and found that it is an appropriate strategy to reduce saline stress in plants. Preliminary studies carried out by Henrichsen et al. (2023) for the use of liquid N source for foliar application in oat crops also showed similar results for the use of urea.

CONCLUSIONS

The water volume of 300 L ha^{-1} dissolves the rates of urea, resulting in the expected oat grain yield for the nitrogen rates. The urea dissolution time increases as the urea rates are increased and the air temperature facilitates its dissolution.

The use of the technology of urea dissolved in water for foliar application results in similar yields to the application of urea to the soil, making it an alternative for the supply of nitrogen in oat crop systems.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Atahar A, Mafy NN, Rahman MM, Mollah MYA, et al. (2019). Aggregation of urea in water: Dynamic light scattering analyses. *J. Mol. Liq*. 294: 1-6. https://doi.org/10.1016/j.molliq.2019.111612.

Azeem B, Kushaari K, Man ZB, Basit A, et al. (2014). Review on materials & methods to produce controlled release coated urea fertilizer. *J. Control. Release*. 181: 11-21. https://doi.org/10.1016/j.jconrel.2014.02.020.

Bárta RL, Silva JAG, Daronco CR, Pretto C, et al. (2021). Qualidade da água para consumo humano no Brasil: revisão integrativa da literatura. *Vig. Sanit Debate.* 9 (4): 74-85. https://doi.org/10.22239/2317-269x.01822.

Basso NCF, Babeski CM, Heusner LB, Zardin NG, et al. (2022). The production without pesticides in the control of oat foliar diseases: resistance inducer by silicon and potassium and escape zone. *Research, Soc. and Develop.* 11 (8): e47611831191. https://doi.org/10.33448/rsd-v11i8.31191.

Bazzo JHB, Garcia EB, Cardoso CP and Zucareli C (2020). Qualidade fisiológica de sementes de trigo em resposta a diferentes doses de nitrogênio via solo e foliar. *Rev. Terra & Cultura.* 36 (70).

Bernis DJ and Viana OH (2015). Influência da aplicação de nitrogênio via foliar em diferentes estágios fenológicos da soja. *Rev. Cultiv. Saber*. 83-92.

Catiavala HSA, Tchilata PN, Pinto CAR, Agostinho FV, et al. (2023). Concepções dos estudantes do curso de licenciatura em ensino da química no isced-huíla sobre os conceitos de solução, soluto e solvente. *RECIMA21-Rev. Cient. Multidi. -ISSN 2675-6218*. 4 (1): e412613-e412613. https://doi.org/10.47820/recima21.v4i1.2613.

Copetti CM, Jung MS, Da Silva JAG, Fachinetto JM, et al. (2022). Biorremediação: metodologia sustentável na remoção de xenobióticos da água. *Research, Soc. and Develo.* 11 (9): e29811931978-e29811931978. https://doi.org/10.33448/rsd-v11i9.31978.

Costa FMAS, Silva AP, Franco Júnior MR and Malagoni RA (2015). Determinação experimental da solubilidade do fertilizante uréia em solventes puros. *Blucher Chem. Engine. Proceed.* 1 (3): 671-676. doi: 10.5151/chemeng-cobeqic2015-423-34041-263310.

Dornelles EF, Da Silva JAG, Carvalho IR, Da Rosa JA, et al. (2023). Artificial Intelligence in the Simulation of Fungicide Management Scenarios for Satisfactory Yield and Food Safety in oat Crops. *Rev. Gest. Soc. Ambi. -RGSA*. 17 (1): e03161-e03161. https://doi.org/10.24857/rgsa.v17n1-029

Fan K, Zhang Q, Tang D, Shi Y, et al. (2020). Dynamics of nitrogen translocation from mature leaves to new shoots and related gene expression during spring shoots development in tea plants (Camellia sinensis L.). *J. of Plant Nutrit. and Soil Sci.* 183 (2): 180-191. https://doi.org/10.1002/jpln.201900268.

Ferrari M, Cortivo CD, Panozzo A, Barion G, et al. (2021). Comparing Soil vs. Foliar nitrogen supply of the whole fertilizer dose in common wheat. *Agronomy*. 11 (11): 2138. https://doi.org/10.3390/agronomy11112138.

Henrichsen L, Da Silva JAG, Basso NCF, Da Rosa JA, et al. (2023). Liquid source nitrogen as a more sustainable technology for oat fertilization with computational simulation resource. *RGSA – Rev. de Gest. Soc. e Ambi.* 17 (2):1-19. https://doi.org/10.24857/rgsa.v17n2-008.

Henrichsen L, Da Silva JAG, Basso NCF, Fachinetto J, et al. (2022). Oat productivity by root and foliar nitrogen uptake in cropping systems. *Austr. Jour.l of Crop Sci.* 16 (10): 1144-1151. doi: 10.21475/ajcs.22.16.10.p3634.

House KA and House JE (2017). Thermodynamics of dissolution of urea in water, alcohols, and their mixtures. *J. of Mol. Liq.* 242: 428-432. https://doi.org/10.1016/j.molliq.2017.07.020.

Ju Z, Liu K, Zhao G, Ma X, et al. (2022). Nitrogen Fertilizer and Sowing Density Affect Flag Leaf Photosynthetic Characteristics, Grain Yield, and Yield Components of Oat in a Semiarid Region of Northwest China. *Agronomy*. 12 (9): 2108. https://doi.org/10.3390/agronomy12092108.

Khan P, Memon MY, Imtiaz M and Aslam M (2009). Response of wheat to foliar and soil application of urea at different growth stages. *Pak. J. Bot.* 41 (3): 1197-1204.

Kraisig AR, Da Silva JAG, Carvalho IR, De Mamann ÂTW, et al. (2020). Time of nitrogen supply in yield, industrial and chemical quality of oat grains. *Rev. Bras. de Engen. Agrí. e Ambi.* 24: 700-706. https://doi.org/10.1590/1807-1929/agriambi.v24n10p700-706.

Mafy NN, Afrin T, Rahman MM, Mollah MYA, et al. (2015). Effect of temperature perturbation on hydrogen bonding in aqueous solutions of different urea concentrations. *Rsc Advances*. 5 (73): 59263-59272. doi: 10.1039/C5RA10718K.

Mantai RD, Da Silva JAG, Carbonera R, Carvalho IR, et al. (2021b). Technical and agronomic efficiency of nitrogen use on the yield and quality of oat grains. *Rev. Bras. de Engen. Agrí. e Ambi.* 25 (8): 529-537. https://doi.org/10.1590/1807-1929.

Mantai RD, Da Silva JAG, Carvalho IR, Lautenchleger F, et al. (2021a). Contribution of nitrogen on industrial quality of oat grain components and the dynamics of relations with yield. *Austr. J. of Crop Sci.* 15 (3): 334-342. Doi: 10.21475/ajcs.21.15.03.p2592.

Mantai RD, Da Silva JAG, Sausen AT, Costa JS, et al. (2015). A eficiência na produção de biomassa e grãos de aveia pelo uso do nitrogênio. *Rev. Bras. de Engen. Agrí. e Ambi.* 19 (4): 343-349. https://doi.org/10.1590/1807-1929/agriambi.v19n4p343-349.

Marolli A, Da Silva JAG, Da Rosa JA, Rasia LA, et al. (2021). A combination of regression and internal point methods as a hybrid model for estimating oat plant productivity. *Gen. and Mol. Res.* 20 (2): 1-16. doi:http://dx.doi.org/10.4238/gmr18756.

Marolli A, Da Silva JAG, Sawick S, Binelo MO, et al. (2018). A simulação da biomassa de aveia por elementos climáticos, nitrogênio e regulador de crescimento. *Arq. Brasi. de Medic. Vet. e Zootec.*70 (2): 535–544. https://doi.org/10.1590/1678-4162-9504.

Martínez-Dalmau J, Berbel J and Ordóñez-Fernández R (2021). Nitrogen fertilization. A review of the risks associated with the inefficiency of its use and policy responses. *Sustainability.* 13 (10): 5625. https://doi.org/10.3390/su13105625

Mortate RK, Nascimento EF, Gonçalves EGS and Lima MWP (2018). Resposta do milho (Zea mays L.) à adubação foliar e via solo de nitrogênio. *Rev. de Agric. Neotr.* 5 (1): 1-6. https://doi.org/10.32404/rean.v5i1.2202

Niu J, Liu C, Huang M, Liu K, et al. (2021). Effects of foliar fertilization: a review of current status and future perspectives. *J. of Soil Sci. and Plant Nutri.* 21: 104-118. https://doi.org/10.1007/s42729-020-00346-3.

Nóbrega JS, Da Silva TI, Lopes AS, Costa RNM, et al. (2023). Foliar nitrogen fertilization attenuating harmful effects of salt stress on purple basil. *Rev. Brasi. de Engen. Agríc. e Ambi.* 27 (6): 472-479. https://doi.org/10.1590/1807-1929/agriambi.v27n6p472-479.

Oliveira AR, De Jesus JH, Da Silva JG, Ferreira L, et al. (2022). O uso da ureia na nutrição de ruminantes. *Rev.Cient. da Facul. de Educ. e Meio Ambi.* 13: 1-4. doi: http://dx.doi.org/10.31072.

Oliveira DTM, De Andrade CLL, Filho FRC, Teixeira MB, et al. (2023). Avaliação biométrica do uso de diferentes fontes de nitrogênio no milho safrinha. *Braz. Jour. of Sci.* 2(1): 63-71. https://doi.org/10.14295/bjs.v2i1.252.

Petean CC, Filho MT, Galindo FS, Buzetti S, et al. (2019). Polímeros orgânicos com ureia dissolvida e doses de nitrogênio no milho. *Rev. de Ciênc. Agrár.-Amaz. J. of Agric. and Enviro. Sci.* 62. http://dx.doi.org/10.22491/rca.2019.2761.

Polese I, Lajús CR, Cericato A, et al. (2018). NDVI e rendimento da cultura do milho submetida a diferentes fontes nitrogenadas. *Anu. Pesq. Ext. Unoesc S. Mig do Oes.* 3: e17555-e17555.

Reginatto DC, Da Silva JAG, Carvalho IR, Lautenchlegere F, et al. (2021). Nitrogen management at sowing and topdressing with the time of supply in the main biotype of oats grown in southern Brazil. *Austr. J. of Crop Sci.* 15 (4): 524-530. 10.21475/ajcs.21.15.04.p2803.

Santos JB, Silva AN, Cruz JO, Dos Santos RB, et al. (2020). Características agronômicas e avaliação econômica do milho sob diferentes doses de nitrogênio na forma de ureia comum e peletizada. *Agri-Enviro. Sci.* 6:10-10. https://doi.org/10.36725/agries.v6i0.3561.

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, et al. (2018). *Brazi. Soil Classif. Syst.* 5th ed. Brasília, DF: Embrapa.

Shnidman L and Sunier AA (1931). The Solubility of Urea in Water. *The J. of Phys. Chemi.* 36 (4): 1232–1240. https://doi.org/10.1021/j150334a013.

Silva JAG, Neto CJG, Fernandes SBV, Mantai RD, et al. (2016). Nitrogen efficiency in oats on grain yield with stability. *Rev. Bras. de Engen. Agríc. e Ambi.* 20 (12): 1095-1100. https://doi.org/10.1590/1807-1929/agriambi.v20n12p1095-1100.

Trautmann AP, Da Silva JAG, Carvalho IR, Colet CDF, et al. (2022). Sustainable nitrogen efficiency in wheat by the dose and mode of supply. *Rev. Bras. de Engen. Agríc. e Ambi*. 26(9): 670-679. https://doi.org/10.1590/1807-1929/agriambi.v26n9p670-679.

Trautmann APB, Da Silva JAG, Da Rosa JA, Carvalho IR, et al. (2021). The supply of nitrogen fertilizer in wheat to the highest environmental quality with satisfactory yield. *Genet. Mol. Res*. 20 (3):1-16. http://dx.doi.org/10.4238/gmr18903.

Yamamoto CF, Pereira EI, Mattoso LH, Matsunaka T, et al. (2016). Slow release fertilizers based on urea/urea–formaldehyde polymer nanocomposites. *Chemi. Engine. J.* 287: 390-397. https://doi.org/10.1016/j.cej.2015.11.023.
