Electrical conductivity based algorithm for precise application of liquid nitrogenous fertilizers

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ABSTRACT

Precise application of nitrogenous fertilizers mainly urea ammonium nitrate (UAN) and granular urea (both pure and neem-coated) in aqueous form, is critically important for basal and foliar applications. The physicochemical properties of aqueous solution of these nitrogenous fertilizers plays important role in design of any liquid fertilizer application system. The study was carried out during 2019–20 at ICAR-Indian Agricultural Research Institute, New Delhi with an aim to develop algorithms for use in sensors-based systems for real time monitoring of available N concentration in the fertilizer solution before its application. The physicochemical properties like pH, electrical conductivity (EC), specific gravity (SG), dynamic viscosity (DV), surface tension (ST) and percentage light absorbance (LA) of urea ammonium nitrate (UAN-28%), pure urea, and neem coated urea in diluted form (pre-selected N-concentrations i.e. 0.78, 0.9, 1.08, 1.33, 1.75, 2.54 and 4.67% corresponding to the dilution ratios of 1:35, 1:30, 1:25, 1:20, 1:15, 1:10 and 1:05) were measured and analyzed for their significance with N-concentration. Electrical conductivity (EC) alone showed a significant relationship with N-concentration. Prediction models were developed for diluted UAN and granular urea fertilizers based on the EC and N-concentrations. The regression models in terms of EC to predict N-concentration had coefficients of determination (R²) of 0.998, 0.998, and 0.999 for diluted UAN, pure urea, and neem coated urea with water, respectively showed a great potential for their sensor based precise application. The controlled application of diluted liquid fertilizers with water can be achieved through sensing relevant physicochemical property.

Keywords: Electrical conductivity, Liquid nitrogenous fertilizers, Regression model

A nitrogenous fertilizer plays a significant role in agricultural production and productivity. It serves as the most essential input to satisfy nutrient requirements during various crop growth stages (Zhai 2006, Zhao and Yu 2006). Since, response of plant depends on the fertilizer rate, form, concentration and frequency of application (Fernández et al. 2013). Nitrogenous fertilizer diluted with suitable dilution ratio with water makes nutrient readily available for the plant intake and have higher nitrogen use efficiency and efficacy than solid fertilizers (Walsh et al. 2016). In hydroponically-grown plants, the nutrient solution with extremely low concentrations leads to growth inhibition. On the other hand, extremely high concentration causes osmotic stress, ionic toxicity, and growth restriction (Savvas et al. 1999). Additionally, in case of foliar application, higher concentration leads to leaf burning due to scorching (Castro et al. 2022). Therefore, both rate and form of application of nitrogenous fertilizer are equally important for any sustainable crop production system.

The physicochemical properties have many applications in precision agriculture-based technologies (Othaman et al. 2019, Darmawan et al. 2023). Also, most of the sensor-based flow control systems rely on physicochemical properties, have proven their usefulness in sensing, monitoring, and controlling different chemical application systems (Sowmiya et al. 2017, Xu et al. 2019). Therefore, the relation between physicochemical properties with concentration and assessment of the feasibility of nitrogenous fertilizers such as urea ammonium nitrate (UAN), pure urea and neem-coated urea, for their basal/foliar application particularly with precision agro-machines is of prime importance.

This study aims to address the existing gap by analyzing the physicochemical properties of liquid nitrogenous fertilizers (UAN, pure urea, and neem-coated urea) at varying nitrogen concentrations, and develop algorithm based on the observed relationships between electrical conductivity and N-concentration to be use in the sensor-based metering systems. Although, the volumetric calibration of nutrient application relies on the relationship between
concentration levels and their corresponding electrical conductivity. This research will provide valuable insights into optimizing different nutrients management practices. Also, it has the potential to significantly benefit small and marginal farmers, allowing them to optimize inputs and contribute to sustainable crop production.

**MATERIALS AND METHODS**

The study was carried out during 2019–20 at ICAR-Indian Agricultural Research Institute, New Delhi. Three liquid fertilizers i.e. UAN, pure urea and neem-coated urea were selected for the study. The composition of the selected liquid fertilizers with their physicochemical properties is listed in (Supplementary Table 1). Initially, the urea fertilizers were in solid form containing 46% N, diluted and converted into aqueous solutions (28% N) equivalent to the UAN (28% N). It helped in reducing the salt problems and maintaining the same level of N concentration in all three liquid fertilizers.

**Preparation of samples for lab study:** According to previous research findings and agronomic practices, the nitrogen concentration for basal and foliar application should not exceed 3% (Walsh et al. 2016, Sundaram et al. 2018). Keeping the above fact in view, the liquid fertilizers i.e. UAN, pure urea and neem coated urea, were diluted with distilled water in the ratios (fertilizer: water) of 1:05, 1:10, 1:15, 1:20, 1:25, 1:30, 1:35, to prepare the sample solutions having different N concentrations, viz. 4.67, 2.54, 1.75, 1.33, 1.08, 0.90 0.78%, respectively. Thereafter, physicochemical properties i.e. specific gravity (SG), dynamic viscosity (DV), surface tension (ST), pH, electrical conductivity (EC), and percentage light absorbance (LA), of all three liquid fertilizers were determined at each N concentration level. The main aim of the study was to determine the effect of nitrogen concentration on physicochemical properties, their feasibility in design of metering systems and select the most significant one for development of physicochemical properties-based N prediction model.

**Determination of physical properties**

**Specific gravity (SG):** SG of liquid fertilizer solutions was determined by density bottle method and calculated as:

\[
\text{Specific gravity} = \frac{W_3 - W_1}{W_2 - W_1}
\]

where \(W_1\), Weight of empty density bottle along with stopper (g); \(W_2\), Weight of water filled density bottle with stopper (g); \(W_3\), Weight of fertilizer solution filled density bottle with stopper (g).

**Dynamic viscosity (DV):** The viscosity refers to the resistance of fluid to flow. It was determined by Ostwald’s viscometer method by determining the time required to flow for the liquid from upper mark A of the bulb of right limb to lower mark B through the capillary tube. The viscosity \(\eta_1\) of fertilizer solution was determined as:

\[
\eta_1 = \frac{\rho_1 t_1}{\rho_2 t_2} \eta_2
\]

where \(\eta_1\) and \(\eta_2\), Viscosity of test liquid (fertilizer solution) and reference liquid (distilled water), respectively; \(\rho_1\) and \(\rho_2\), Density of test liquid (fertilizer solution) and reference liquid (distilled water), respectively; \(t_1\) and \(t_2\), Time of flow of test liquid (fertilizer solution) and reference liquid (distilled water), respectively.

**Surface tension (ST):** ST of liquid fertilizer solutions having different N concentrations was found by drop weight method (Tate 1864) forming cylindrical drops at the tip of a stalagmometer nozzle by following standard procedure. Surface tension (\(\sigma\)) was calculated as:

\[
\sigma (\text{N/m}) = \frac{W}{2\pi r}
\]

where \(r\), Radius of the tip of the stalagmometer i.e. 0.75 \times 10/m; \(W\) (kg), Mean weight of the single drop of the liquid = \(W_2 - W_1\)

**Determination of chemical properties**

**pH and electrical conductivity (EC):** pH and EC of fertilizer solution were determined by potentiometric and electrometric methods using digital pH and EC meter, respectively. The calibration of pH meter was done by the standard buffer solutions of pH 4 and pH 7 while EC meter was calibrated by using KCl (0.01 M) solution.

**Light absorbance (LA):** The instrument used for the measurement of percentage LA was digital spectrophotometer. The distilled water having 0% LA was used as a reference liquid. Sample to be measured was inserted between the spectrometer and photometer and the light of wavelengths 470 nm was passed through the solution. The percentage absorbance of the emitted light displayed by the spectrophotometer was recorded. All the experiments were conducted by following standard procedures and replicated thrice to reduce the error in the measurements.

**Statistical analysis:** Statistical analysis was carried out in two stages. In first, one-way ANOVA performed for completely randomized block design (CRBD) using Minitab software to interpretate the treatment main effects on physicochemical properties of all three liquid fertilizers. Tukey’s test was used to study the significance among different response combinations. In the later stage, polynomial regression models were developed for all three fertilizers by using the programming language Python in Google Collaboratory.

**RESULTS AND DISCUSSION**

Urea (NH\(_2\)CONH\(_2\)), when dissolved in water converted into ammonium (NH\(_4^+\)) and cyanate (CNO\(^-\)) ions (Alexandrova and Jorgensen 2007), while urea ammonium nitrate [(NH\(_2\))\(_2\)CO · NH\(_4\)NO\(_3\)] in aqueous form yields ammonium (NH\(_4^+\)) and nitrate (NO\(_3^−\)) ions (Wahab and Mahiuddin 2001). These NH\(_4^+\) and NO\(_3^−\) ions serve as important sources of nitrogen for plants. The ionic concentration when varied with dilution of liquid fertilizers in water, affect the physicochemical properties of the aqueous solution. The change in physicochemical properties with N concentration is of critically important for design
of any basal and foliar application systems as well as in green/poly house protected crops. Although, macro and micro-nutrients applied in hydroponic cultivation practices through different fertilizer products, became available for the plant in ionic form i.e. NO$_3^-$, NH$_4^+$, SO$_4^{2-}$, H$_2$PO$_4^-$, K$^+$, Ca$^{2+}$, Mg$^{2+}$, Zn$^{2+}$ etc. (Sanchez et al. 2021). The level of ionic concentration of plant nutrients affects the physical as well chemical properties like pH and EC of liquid and aqueous solution of fertilizer (Shawon et al. 2023). Keeping this fact in mind, the algorithm based on physicochemical properties and concentration level is practically viable to developed for multiple nutrients application system.

**Effect of N concentration on physical properties of liquid fertilizers:** Specific gravity measures the density of a substance in comparison to the density of water. The SG of aqueous solution of all three liquid fertilizers increased with increasing the N concentration. It was in the range of 0.99–1.056 for UAN, 0.983–1.018 for pure urea, and 0.980–1.029 for neem coated urea, respectively (Table 1). Results of the present study are in agreement with Makarov and Egorov (2018) who found that density/specific gravity of aqueous solution of UAN and urea fertilizers increased with increasing N concentration. It was also found that, variation of SG was not significant for each N concentration in case of UAN and pure urea, while overall effect of N concentration on SG was significant for all three fertilizers at 5% level of significance (Table 2). Also, SG was in closer proximity at each N concentration level, and within close range as that of water for all three liquid fertilizers.

Viscosity is a measure of fluid’s resistance to flow. The dynamic viscosity was increasing with increase in N concentration and vice versa. The maximum dynamic viscosity of 1.203 mPa-sec was found for UAN at 4.67% N concentration while the minimum dynamic viscosity of 0.850 mPa-sec was found for pure urea at 0.78% N concentration (Table 1). Like specific gravity, variations in dynamic viscosity measured at different N concentrations were not significant (Table 1), but the overall effect was significant at 5% level of significance (Table 2). Kawahara and Tanford (1966) reported same variation in density and viscosity of urea solution with different concentration.

Similarly, the significant increments in surface tension of neem coated urea solution were observed with increase in N concentration from 0.78–4.67% at 5% level of significance (Table 1). While in other two, ST values were non-significant in some N concentration levels but the overall effect was significant in case of all three liquid fertilizers (Table 2). At lower concentration (<1.33% N), the surface tension of liquid fertilizer was found close to that of pure water. Helonen et al. (2017) found the similar variation while studying urea-water solution properties (density, viscosity and surface tension) in an undersaturated solution. Kapusta et al. (2019) reported the same physical properties of urea water solution in their study.

**Effect of N concentration on chemical properties of liquid fertilizers: pH, EC and LA indicate the ionic concentration (NH$_4^+$, CNO, NO$_3^-$) in the aqueous solutions of the liquid fertilizers. The results revealed that, pH of aqueous solution of UAN decreased with increasing N concentration due to acidic nature of NH$_4^+$ ions. On the other hand, slight increase in pH of aqueous solution fertilizer was observed with increased N concentration in case of both urea and Neem coated urea.**

![Table 1 Specific gravity, dynamic viscosity and surface tension of the liquid fertilizers at different N-concentrations](image)

<table>
<thead>
<tr>
<th>N-concentration (%)</th>
<th>Specific gravity (SG)</th>
<th>Dynamic viscosity (DV) (mPa-sec)</th>
<th>Surface tension (ST) (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UAN</td>
<td>Pure urea</td>
<td>Neem coated urea</td>
</tr>
<tr>
<td>0.78</td>
<td>0.996$^a$</td>
<td>0.983$^a$</td>
<td>0.980$^a$</td>
</tr>
<tr>
<td>0.9</td>
<td>1.007$^{ab}$</td>
<td>0.984$^a$</td>
<td>0.987$^b$</td>
</tr>
<tr>
<td>1.08</td>
<td>1.014$^{bc}$</td>
<td>0.987$^b$</td>
<td>0.993$^c$</td>
</tr>
<tr>
<td>1.33</td>
<td>1.027$^{bc}$</td>
<td>0.996$^c$</td>
<td>0.999$^d$</td>
</tr>
<tr>
<td>1.75</td>
<td>1.022$^{cd}$</td>
<td>1.006$^d$</td>
<td>1.009$^e$</td>
</tr>
<tr>
<td>2.54</td>
<td>1.032$^{de}$</td>
<td>1.012$^e$</td>
<td>1.017$^f$</td>
</tr>
<tr>
<td>4.67</td>
<td>1.056$^{e}$</td>
<td>1.018f</td>
<td>1.029$^g$</td>
</tr>
</tbody>
</table>

$^a$Mean follows the same letter(s) within N-concentration are not significantly different at 5% level of significance. UAN, Urea ammonium nitrate.

![Table 2 ANOVA for physicochemical properties of selected liquid fertilizers at different N-concentrations](image)

<table>
<thead>
<tr>
<th>Liquid fertilizer</th>
<th>SG</th>
<th>DV</th>
<th>ST</th>
<th>pH</th>
<th>EC</th>
<th>LA</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAN</td>
<td>F value</td>
<td>P value</td>
<td>F value</td>
<td>P value</td>
<td>F value</td>
<td>P value</td>
</tr>
<tr>
<td>Pure urea</td>
<td>77.87</td>
<td>&lt;.05</td>
<td>113.50</td>
<td>&lt;.05</td>
<td>604.39</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Neem coated urea</td>
<td>1566.83</td>
<td>&lt;.05</td>
<td>1069.03</td>
<td>&lt;.05</td>
<td>3877.01</td>
<td>&lt;.05</td>
</tr>
</tbody>
</table>

SG: Specific gravity; DV: Dynamic viscosity (mPa-sec); ST: Surface tension (mN/m); pH: Potential of hydrogen; EC: Electrical conductivity; LA: Light adsorbance (%).
Table 3 The potential of hydrogen, electrical conductivity and light absorbance of the liquid fertilizers at different N-concentrations

<table>
<thead>
<tr>
<th>N-concentration (%)</th>
<th>Potential of hydrogen (pH)</th>
<th>Electrical conductivity (EC) (µS/cm)</th>
<th>Light absorbance (LA) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UAN</td>
<td>Pure urea</td>
<td>Neem coated urea</td>
</tr>
<tr>
<td>0.78</td>
<td>6.783&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.073&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.066&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.9</td>
<td>6.770&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.080&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.086&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>1.08</td>
<td>6.750&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.126&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.120&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>1.33</td>
<td>6.453&lt;sup&gt;c&lt;/sup&gt;</td>
<td>7.183&lt;sup&gt;c&lt;/sup&gt;</td>
<td>7.196&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>1.75</td>
<td>6.323&lt;sup&gt;c&lt;/sup&gt;</td>
<td>7.457&lt;sup&gt;d&lt;/sup&gt;</td>
<td>7.291&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>2.54</td>
<td>6.140&lt;sup&gt;d&lt;/sup&gt;</td>
<td>7.813&lt;sup&gt;e&lt;/sup&gt;</td>
<td>7.456&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>4.67</td>
<td>5.647&lt;sup&gt;e&lt;/sup&gt;</td>
<td>7.943&lt;sup&gt;f&lt;/sup&gt;</td>
<td>7.700&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>*Mean follows the same letter(s) within N-concentration are not significantly different at 5% level of significance. UAN, Urea ammonium nitrate.</sup>
1–5%. The physical properties like SG, DV and ST of the liquid fertilizers are considered most important properties in design of any flow control system, were found close to that of pure water. On the other hand, chemical properties like pH, EC and LA were used as an indicator in the development of algorithms to real time monitor the N concentration in automatic and precise liquid fertilizer application system. In this study, data revealed that the values of EC showed the close relation with N concentration. Therefore, the relationship between EC and N concentration was best described using a third-degree polynomial equation. The developed prediction models for all three liquid fertilizers: UAN, aqueous urea and aqueous neem coated urea, paved the way to use the EC as an indicator in any automatic monitoring and controlled application system of liquid nitrogenous fertilizers.

REFERENCES


