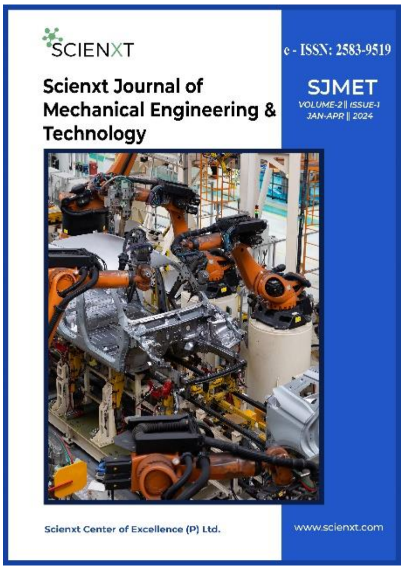

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Investigation and optimization of urea-water droplet evaporation characteristics for enhanced agricultural and automotive applications

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Abstract:

The Taguchi Orthogonal Signal-to-Noise Ratio (TOPSIS) method is utilized in this study to conduct multi-objective optimization of process parameters in urea solution-containing droplets. By systematically exploring experimental conditions, the study identifies the top three optimal experiments, emphasizing specific substrate materials, temperatures, plate thicknesses, and plate angle orientations. Notably, optimal values for evaporation time and minimum droplet deposition weight are discerned, with a focus on aluminum as a substrate, a temperature of 110 °C, a plate thickness of 1 mm, and a plate angle orientation of 40°. These results offer valuable insights into refining the manufacturing process for droplet-containing urea solutions, thereby enhancing efficiency and performance.

Keywords:

TOPSIS method, Multi-objective optimization, Droplet-containing urea, Process parameter optimization

1. Introduction:

Research into evaporation processes, particularly in solutions like urea and water, holds significant importance for both industrial applications and environmental systems. This paper aims to delve into the dynamics of urea-water droplet evaporation, with a specific focus on integrating the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) technique for optimization.

The impetus for this study originates from the widespread agricultural utilization of urea-water solutions as fertilizers. As sustainable agricultural practices gain momentum, there is a pressing need to comprehend and optimize the evaporation process to enhance nutrient delivery and mitigate environmental impact. Furthermore, in automotive Selective Catalytic Reduction (SCR) systems, optimizing urea-water solution (UWS) evaporation is crucial for effectively reducing nitrogen oxides (NOx) emissions. Given the challenges posed by confined space and varying operating conditions in automotive SCR systems, precise control of UWS injection and evaporation is imperative for optimal performance. Additionally, the study explores evaporative self-assembly, a phenomenon where nonvolatile solutes precipitate onto a solid surface during evaporation. Inspired by the coffee-ring effect, this process finds applications in diverse fields such as microfluidic devices, biotechnology, and inkjet printing. Understanding the underlying mechanisms of evaporation-induced self-assembly contributes to the development of novel assembly methods.

The objectives of this research encompass investigating the evaporation characteristics of urea-water droplets, analyzing the influence of parameters like concentration and temperature on the evaporation process, and optimizing the process using the TOPSIS technique. By addressing these objectives, the study endeavors to augment our comprehension of evaporation processes in urea-water solutions and facilitate the advancement of more efficient and sustainable agricultural and automotive technologies.

2. Methodology:

The study commences by converting experimental observations into a decision matrix, employing evaporation time and droplet deposit weight measurements as key parameters. Normalization methods are employed to ensure equitable comparison across various experimental settings. The weighted and normalized decision matrix is then utilized to identify the Positive Ideal Solution (V+) and Negative Ideal Solution (V-), corresponding to optimal and worst-case scenarios, respectively. Subsequently, the separation distances for each solution are computed, followed by the determination of the overall performance score using TOPSIS equations.

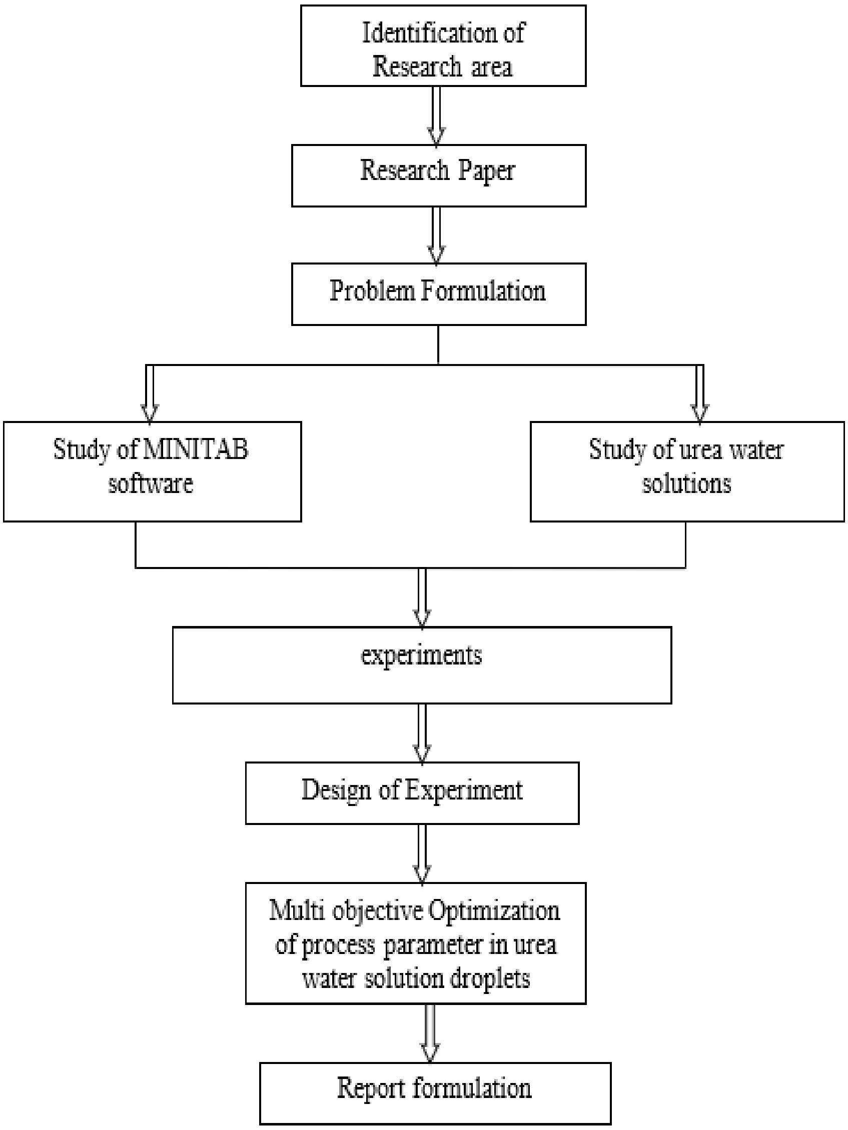

Figure. 1: Research path adopted

3. Experimental details:

The experimental setup depicted in Fig. 2 involves observing the evaporation behavior of a droplet (urea solution) on three distinct surfaces with differing heat conductivity properties. A precise volume of pure liquid is dispensed onto each surface using a device capable of maintaining consistent distribution. The chosen substrates include Aluminum (Al), Mild Steel (MS), and glass, each characterized by varying heat conductivity values. All specimens share uniform dimensions of 1.2cm x 1.2cm x 0.1cm (length x width x thickness). The droplet composition comprises a water solution containing urea. Table. 3.3 presents the recorded contact angles for different concentrations of the urea-water solution. Experimental trials were conducted under an air pressure of 99.2KPa, with ambient temperatures and relative humidity levels controlled within the chamber by adjusting the power output of the illuminating bulb to three different levels: 100W, 200W, and 260W. The experimental design adhered to the specifications outlined in Table. 1.

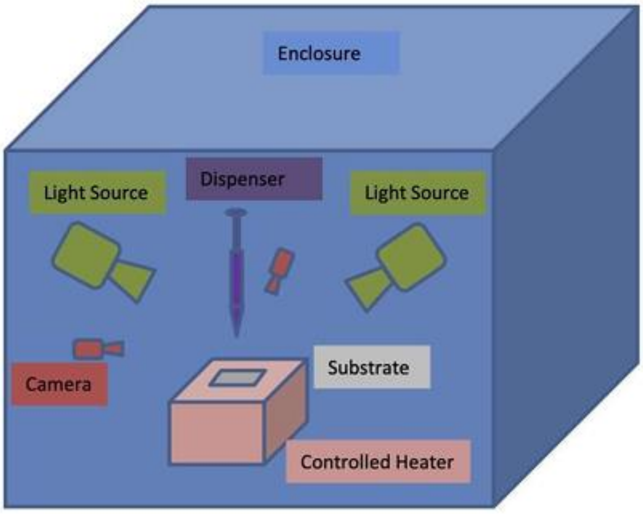

Figure. 2: Experimental setup

Table. 1: Experimental Result

Exp No	Input parameter				Output parameter	
	Substrate (S)	Temperature	Plate thickness	plate angle orientation	evaporation time (sec)	deposit weight (gm)
1	Al	110	1	0	0.69	2.07
2	Al	110	1	0	0.64	2.03
3	Al	110	1	0	0.52	1.99
4	Al	120	1.5	20	0.42	2.03
5	Al	120	1.5	20	0.4	2.06
6	Al	120	1.5	20	0.49	1.99
7	Al	130	2	40	0.49	1.99

8	Al	130	2	40	0.49	1.99
9	Al	130	2	40	0.54	1.99
10	MS	110	1.5	40	0.54	1.99
11	MS	110	1.5	40	0.49	1.99
12	MS	110	1.5	40	0.52	1.99
13	MS	120	2	0	0.49	1.99
14	MS	120	2	0	0.52	1.99
15	MS	120	2	0	0.54	1.99
16	MS	130	1	20	0.47	2
17	MS	130	1	20	0.52	1.99
18	MS	130	1	20	0.49	1.99
19	Glass	110	2	20	0.54	1.99
20	Glass	110	2	20	0.54	1.99
21	Glass	110	2	20	0.49	1.99
22	Glass	120	1	40	0.49	1.99
23	Glass	120	1	40	0.54	1.99
24	Glass	120	1	40	0.62	2.01
25	Glass	130	1.5	0	0.62	2.01
26	Glass	130	1.5	0	0.68	3.05
27	Glass	130	1.5	0	0.78	2.03

4. Topsis optimization:

Hwang and Yoon [1] introduced a method called the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to address Multiple Criteria Decision Making (MCDM) problems. They proposed the concepts of the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) to aid in determining the shortest Euclidean distance for ranking alternatives. According to their approach, each criterion must be either maximized or minimized. TOPSIS aims to rank alternatives based on their proximity to the optimal ideal solution among the available options. The best alternative is assigned a rank of one, while the worst alternative approaches rank zero. Intermediate rankings are assigned to other alternatives based on their relative distances from the best and worst solutions. By employing a consistent set of criteria, TOPSIS allows for accurate assessment of the relative merits of each alternative, thereby identifying the most alarming issues requiring attention.

The TOPSIS technique involves several steps. It views an MCDM problem with m alternatives as a geometric system with m points in an n-dimensional space [2]. The fundamental principle of this method is to select the alternative that minimizes the geometric distance from the PIS while maximizing the distance from the NIS [3]. In order to implement TOPSIS [4], it is commonly assumed that criteria should exhibit monotonic behavior (either increasing or decreasing) to facilitate the identification of the PIS and NIS.

Step 1: Establishment of DM

Construct the decision matrix as follows

$$DM = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_p \end{matrix} \begin{bmatrix} R_1 & R_2 & \cdots & R_q \\ c_{11} & c_{12} & \cdots & c_{1q} \\ c_{21} & c_{22} & \cdots & c_{2q} \\ \vdots & \vdots & \ddots & \vdots \\ c_{p1} & c_{p2} & \cdots & c_{pq} \end{bmatrix} \quad 1$$

Step 2: The significance of each response pertaining to the evaporation time, deposit weight, and relies on the configuration of the diction holder.

Step-3: The weighted normalized decision matrix is obtained by multiplying the normalization matrix with its corresponding weights. The equation used to calculate the weighted normalized decision matrix is as follows.

$$V\_ij = X\_ij \times W\_j \quad 2$$

For values of i ranging from 1 to m and j ranging from 1 to n, the symbol w_ij denotes the weight assigned to the jth attribute.

Step-4: The positive ideal solution (V+) represents the optimal value, while the negative ideal solution (V-) signifies the least favorable value for each attribute in the weighted decision matrix, determined as follows.

$$V^+ = (V_1^+, V_2^+, \cdots \cdots V_n^+) \text{Maximum values} \quad 3$$

$$V^- = (V_1^-, V_2^-, \cdots \cdots V_n^-) \text{Minimum values} \quad 4$$

Step-5: The separation distance for each solution, specifically the positive ideal solution (S+) and the negative ideal solution (S-), is computed using the following equation.

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5} \qquad 5$$

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j\right)^2\right]^{0.5} \qquad 6$$

Step-6: Compute the Performance Score using the following equation.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \qquad 7$$

Step 7: Ranking the performance scores is done based on the ascending order of the closeness-coefficient values.

5. Results and discussion:

This study employs the TOPSIS approach to optimize the process parameters of urea-water solution droplets with multiple objectives. The objective of this approach is to derive a single numerical value by evaluating the measurements of evaporation time and droplet deposit weight. Initially, the obtained findings are organized into a decision matrix based on the data provided in Table. 2. Subsequently, the normalization of the matrix is performed using Equation 1, resulting in the Normalized matrix as depicted in Table. 2. The attributes related to evaporation time and droplet deposit weight are considered to possess lower values. The process of obtaining the Normalizing weight matrix involves applying Equation 2, resulting in the matrix shown in Table 3. The decision maker has identified the Positive Ideal Solution (V+) and Negative Ideal Solution (V-).

Step 1: Normalization of experimental result

Step 2: The weight of each response for Evaporation time and Deposit weight of droplet are 0.5, and 0.5 respectively.

Step-3: The calculation of the weighted normalized decision matrix involves multiplying the normalization matrix by its corresponding weights as per equation 2.

Step-4: Equation 3 and 4 are utilized to determine the positive ideal solution (V+), representing the optimal value, and the negative ideal solution (V-), indicating the worst value for each attribute in the weighted decision matrix.

Step-5: Equations 5 and 6 are employed to calculate the separation distance for each solution, namely the positive ideal solution (S^+) and the negative ideal solution (S^-)

Table. 2: Matrix of separation for all the samples

Exp. No.	Evaporation time Si^+	Deposit weight of droplet Si^-
1	0.006370472	0.282954138
2	0.003669081	0.287877994
3	0.000448062	0.297702439
4	0.007522731	0.297499703
5	0.009001162	0.297545013
6	0.005774483	0.294306913
7	0.012340633	0.287740763
8	0.012340633	0.287740763
9	0.013635167	0.278741182
10	0.021573649	0.270121367
11	0.020812453	0.273926502
12	0.0212432	0.27161745
13	0.030536536	0.26420242
14	0.030967282	0.261893368
15	0.031297731	0.260397284
16	0.043700928	0.2523768
17	0.043693894	0.249166756
18	0.044919185	0.244349977
19	0.064550723	0.221506906
20	0.064550723	0.221506906
21	0.062994543	0.225555106
22	0.089951978	0.198597671
23	0.091508157	0.194549472

24	0.096488671	0.186937903
25	0.146134885	0.137291689
26	0.268998126	0.013550533
27	0.188913134	0.117633041

Step-6: Compute the Performance Score using equation 7 and present the results in

Step 7: Ranking the performance scores is done in accordance with the ascending order of the closeness-coefficient values.

Table. 7: Performance score ranking.

Exp. No.	Pi	Ranking
1	0.977981574	10
2	0.987415133	5
3	0.998497195	1
4	0.975337123	9
5	0.970636848	4
6	0.980756944	2
7	0.958875716	14
8	0.958875716	6
9	0.953364329	8
10	0.926040391	15
11	0.929386825	12
12	0.927463112	3
13	0.89639464	16
14	0.894259327	11
15	0.892703921	7
16	0.852400489	17
17	0.850803125	13
18	0.844714919	18
19	0.774343643	23

20	0.774343643	20
21	0.781685601	19
22	0.688261697	24
23	0.680105867	22
24	0.659563782	21
25	0.484399494	26
26	0.04795823	25
27	0.383736776	27

5.1. Analysis of Variance for performance score evaporation time:

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels which is shown in Table 8. From table 8 it can be observed plate angle orientation affects the evaporation time maximum 19.85 % followed by Substrate material 18.48 %, temperature (inside) 11.10 %. Plate thickness has minimum affect only 4.19 %.

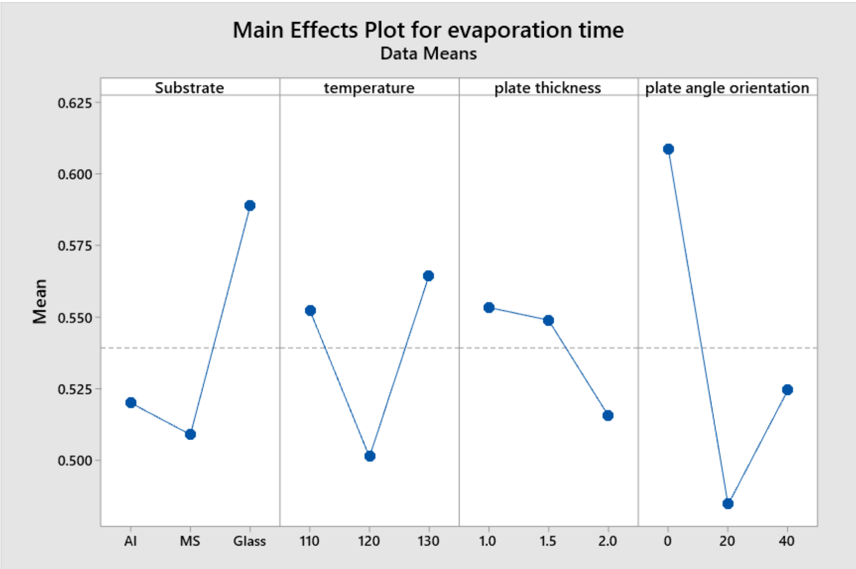

Figure. 3: Effect of process parameters on evaporation time

From Fig. 3 it is observed that the optimum value for evaporation time are aluminium as substrate, with 110 ^{o}C temperature, plate thickness of 1 mm and Plate angle orientation of 40 ^{o}C for optimal value of evaporation time.

5.2. Analysis of Variance for performance score droplet deposit weight:

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in formally testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels which is shown in Table. 9. From table 9 it can be observed plate angle orientation affects the droplet deposit weight maximum 28.85 % followed by Substrate material 19.48 %, temperature (inside) 8.10 %. Plate thickness has minimum affect only 3.19 %.

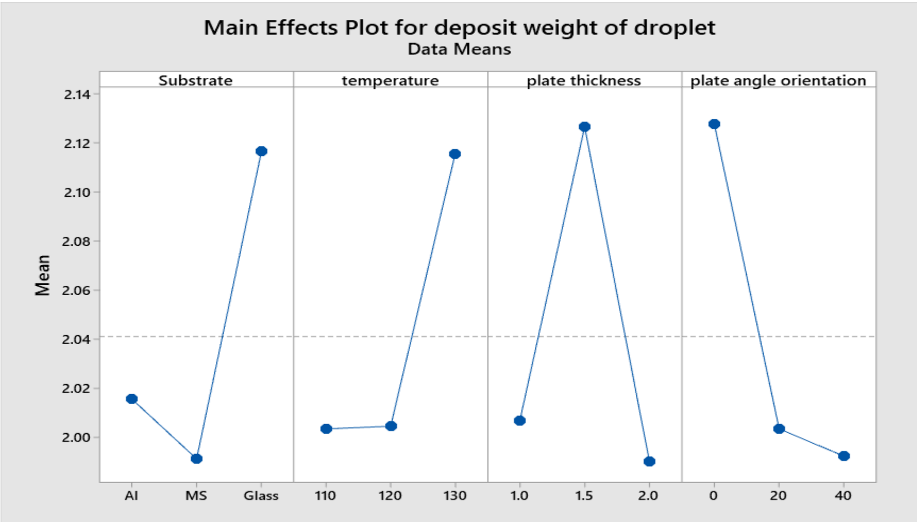

Figure. 5: Effect of process parameters on Droplet deposite weight

From Fig. 5 it is observed that the optimum value for droplet deposited weight minimum are aluminium as substrate, with 110 ^{o}C temperature, plate thickness of 1 mm and Plate angle orientation of 40 ^{o}C.

6. Conclusion:

The TOPSIS method was employed for multi-objective optimization of process parameters in droplet-containing urea solution.

1. The top three optimal experiments for droplet-containing urea were determined as follows:

a. Experiment No. 3: Aluminum substrate, temperature of 110°C, plate thickness of 1 mm, and plate angle orientation of 0°

b. Experiment No. 6: Aluminum substrate, temperature of 120°C, plate thickness of 1.5 mm, and plate angle orientation of 20°

c. Experiment No. 12: Mild Steel substrate, temperature of 110°C, plate thickness of 1.5 mm, and plate angle orientation of 40°.

2. The optimal value for evaporation time was observed to be:

- Aluminum substrate
- Temperature of 110°C
- Plate thickness of 1 mm
- Plate angle orientation of 40°C.

3. The optimal value for minimum droplet deposited weight was observed to be:

- Aluminum substrate
- Temperature of 110°C
- Plate thickness of 1 mm
- Plate angle orientation of 40°C.

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