

## Research Article

# Investigation of the Energy Efficiency of Electrohydrodynamic Drying under High Humidity Conditions

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Electrohydrodynamic (EHD) drying is an emerging drying technology that is based primarily on the phenomenon of ionic discharge between two electrodes. The aim of this study was to experimentally investigate the energy efficiency of the EHD drying based on the corona discharge current. Moreover, we aimed to compare the energy efficiency of the EHD drying with that of other available drying technology options under the condition of high humidity, which mimics Indonesia's environment as a potential target for implementation, given that it is of interest to investigate the feasibility of the EHD drying in a real environment. The results show that the dominant parameters of the EHD drying rate are the corona discharge current and the moisture content zones of the target objects. Findings from this study show that the EHD drying technology could be effectively used to replace the conventional drying process in developing countries having high humidity environments and facing energy consumption challenges.

## 1. Introduction

Electrohydrodynamic (EHD) drying is an emerging technology that has recently gained attention owing to its potentially wide applications in agriculture, especially for drying [1]. In addition to low energy consumption [2], EHD drying also offers various advantages with respect to the quality of the dried product—lower shrinkage [3, 4], preserved color [3–5], and nutrient content [6], and a higher rehydration ratio [3].

The working principle of EHD drying is based primarily on the phenomenon of ionic discharge. Two electrodes are required for the set-up, with a high potential difference applied between them. Ions generated are then transported to the collecting electrode by the influence of the electric force. As the ions move to the other electrode along the electric field, the ions collide with other air molecules, creating a flow of air called an ionic wind [7, 8]. The ionic wind disturbs the saturated boundary layer around target objects and causes water molecules to evaporate from the target objects.

Many researchers have previously attempted to unravel the physics of EHD drying as a conjugate phenomenon interlinking many physical parameters to drying. It is anticipated that an understanding of the relationship between parameters would aid in the industrial implementation of EHD drying. However, many studies have been mostly solitary, which offer only a partial understanding of the phenomenon: the effect of applied voltage on the drying performance [9], the effect of humidity and pressure [10–12], the effect of cross-wind [12–14], the effect of AC current on drying [15], and analysis of the drying of various agricultural products [16–18], to name a few. The effect of electrode geometries on the drying performance has also been widely investigated [3–5, 8, 19, 20]. In the studies, the shape and arrangement of the emitter and collecting electrodes are investigated. This research typically compares three different emitter electrode shapes which are needles, plate, and two different collecting electrodes which are plate and mesh [19].

Recently, Martynenko et al. raised a hypothesis on the importance of the corona discharge current to the drying performance [21]. The authors argued that the mass transfer

is directly proportional to the ionic wind velocity, which is proportional to the current density. Conveniently, the corona discharge current is easily measured; therefore, it can act as a promising parameter to offer insights into the design considerations of EHD drying. In addition, in the same publication [21], which was revised more recently [22], the same group presented a diagram that neatly displayed how various factors relate to each other and how they eventually determine the mass transfer in EHD drying.

Martynenko et al. [21] and Kudra and Martynenko [22] provided critical insights for future development and applications of EHD drying. However, the analysis has not yet been linked to the energy aspect of EHD drying, whereas energy efficiency is a major factor to consider when it comes to potential implementation in real environments. The importance of investigating the energy efficiency of EHD drying is highlighted in a recent review on research about EHD drying [23]. Therefore, in this research, the objective was to investigate the energy efficiency of EHD drying based on the corona discharge current. Several factors were also considered, especially the effect of different moisture contents in the samples on the drying rate. Additionally, it is imperative to consider an energy scenario in a real environment. In this study, we selected Indonesia as a potential target for implementation. Mimicking the condition of high humidity, we then carried out the energy analysis by comparing it with other available off-the-shelf drying technology options, such as hot air grain dryers, to assess the feasibility of EHD drying.

## 2. Materials and Methods

**2.1. Investigation of the Effect of Corona Discharge Current Value on Drying Speed and Energy Efficiency of Drying in EHD Drying.** The aim of this experiment was to investigate the effect of corona discharge current on the drying rate and energy efficiency of EHD drying. Figure 1(a) shows a schematic of the experimental system for EHD drying experiments. The experimental system consisted of a high-voltage electrode with 16 needles integrated on a flat plate (Figure 1(b)), a flat plate-type ground electrode, a high-voltage power supply (HAP-10B10, Matsusada Precision Inc., Shiga, Japan), a precision air conditioner (PAP01B-KJ, ORION Machinery Co., Ltd., Nagano, Japan), and an electronic balance (Practum224-1OJP, Sartorius AG, Göttingen, Germany). The electrodes are  $70 \times 75 \times 2$  mm in size. The voltage electrode had 16 needles spaced 20 mm apart. The interelectrode distance (distance from the tip of the needle to the ground electrode)  $d$  was 20 mm. Multiple needle-like electrodes were chosen among various electrode types, such as single-needle and wire electrodes [18, 24] because multiple needle-like electrodes can be used in industrial settings where a wider area is needed for drying. A Faraday cage was used to prevent stray electromagnetic waves from affecting the measurement.

The corona discharge current generated by the EHD was measured using a digital multimeter (PC773, Sanwa Electric Instrument Co., Ltd., Tokyo, Japan). Samples were prepared

from paddy rice. The experimental procedure for the EHD drying experiment was as follows:

- (1) The dry weight ( $W_{\text{dry}}$ ) of the samples were measured. The dry weight of the sample ( $W_{\text{dry}}$ ) was defined as the weight of the sample when the desiccant (silica gel) was used to sufficiently absorb moisture until measured weight did not change anymore. The sample dry weight was 10 g;
- (2) the samples were soaked in water for 24 h to moisten them until the moisture content was approximately 30% (Figure 1(c));
- (3) the water-impregnated samples were evenly spread on the ground electrode to form a circle of 7.5 cm in diameter. The sample is partially spread over two layers with no gaps; and
- (4) a high voltage was applied while maintaining the temperature and humidity and measuring the change in weight of the sample ( $W_{\text{wet}}$ ).

The moisture content based on wet weight (moisture content)  $MC_{\text{wb}}$  was derived as follows:

$$MC_{\text{wb}} = \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{wet}}} \times 100 (\%). \quad (1)$$

The applied voltages ranged from 0 kV (natural drying) to 4.6 kV~5.8 kV. The corona discharge started around 4.4~4.5 kV. Drying experiments were conducted in 0.1 kV increments from 4.6 kV~5.2 kV and in 0.2 kV increments from 5.2 kV~5.8 kV. Experiments were conducted by changing the applied voltage, and the drying rate (%/h) relative to the measured corona discharge current value was derived for each moisture content zone (high-moisture content zone, 26%~25%; medium-moisture content zone, 21%~20%; low-moisture content zone, 16%~15%). The range was chosen because in Indonesia, the moisture content of paddy rice immediately after harvest is about 25% (rainy season) to 22% (dry season) [25]. The purpose of grain drying is to reduce the moisture content to 15%~14%, which is suitable for storage. The drying rate is a unit used in the field of grain drying to express the rate of drying and is calculated as the decrease in moisture content per unit time. The drying rate per unit of electricity (%/mW·h) was obtained as an indicator of the energy efficiency of drying with the following equation where  $T$  is the measured time needed for evaporating 1% of moisture content (sec),  $V$  is the applied voltage (kV) and  $A$  is the mean value of measured current ( $\mu\text{A}$ ).

$$\frac{\%}{\text{mW} \cdot \text{h}} = \frac{3600/T}{V \times A}. \quad (2)$$

At 5.8 kV, the maximum value of the corona discharge current was  $12.22 \mu\text{A}$ , approaching the order of  $10^{-5}$  A, which is the current value that shifts to glow discharge. The temperature and humidity were kept at  $23.1 \pm 1.6^\circ\text{C}$  and  $50.0 \pm 2.0\%$  relative humidity (RH) during the experiment of the effects of corona discharge current on the drying rate.

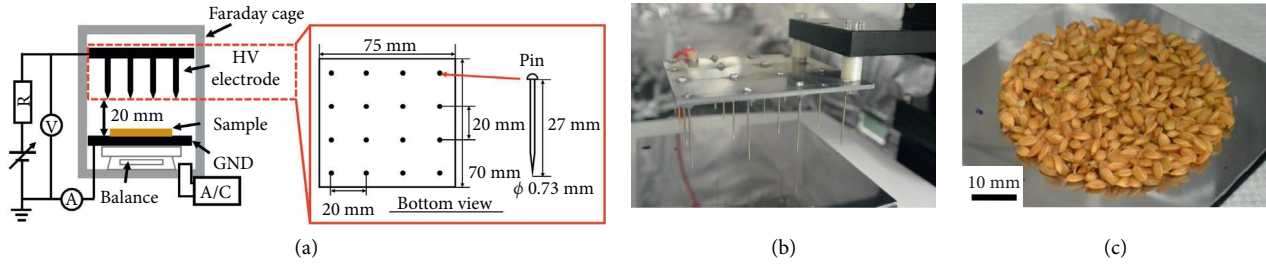


FIGURE 1: (a) Schematic diagram of the experimental set-up; (b) photograph of the electrode; and (c) the target material.

**2.2. Comparison of Drying Performance between the EHD Drying and Conventional Drying Methods under High Humidity Conditions.** Taking the environment of Indonesia as an example of that of a developing country, the experiment compared the drying performance of the EHD drying and conventional drying methods under high humidity conditions. In the postharvest drying of paddy, the drying process was carried out at a drying rate of approximately 0.8 to 1.3%/h to prevent cracking, which is caused by very rapid moisture movement within the grain [26]. Based on the experiment of the corona discharge current, the voltage was set so that the drying rate at a low moisture content (16%~15%) would be within the range of the drying rate. At the low moisture content zone, evaporation of water content from the inside of the paddy is considered the main factor. A sample of paddy rice that had been moistened for 24 h was used. The moisture content of the treatment sample was between 15% and 25%. To simulate a high-humidity environment, the temperature and humidity within the experimental set-up were maintained at  $23.4 \pm 1.4^\circ\text{C}$  and  $68.8 \pm 0.9\%$  RH in the experiment of comparing efficiency between EHD drying and sun drying.

### 3. Result and Discussion

**3.1. Effects of Corona Discharge Current on the Drying Rate.** Figure 2 shows the relationship between the drying rate and the corona discharge current in the moisture content zone. Figure 2 shows that in all moisture content zones, the drying rate increased with increasing corona discharge current, but the increase was moderate. In particular, when the moisture content was low (16%~15%), the dry loss rate remained almost unchanged from a corona discharge current value of approximately  $2.6 \mu\text{A}$ .

The results also suggest that in high-moisture content zones, the relationship between the corona discharge current and drying rate fits the square root approximation, as reported by Kudra and Martynenko [22]. However, in the low-moisture content zones, the relationships were almost constant. This result suggests that the moisture content zones of drying targets play a significant role in determining the drying rate.

Figure 3 shows the relationship between the dry decay rate per unit power and the corona discharge current. The corona discharge current is the average value of each

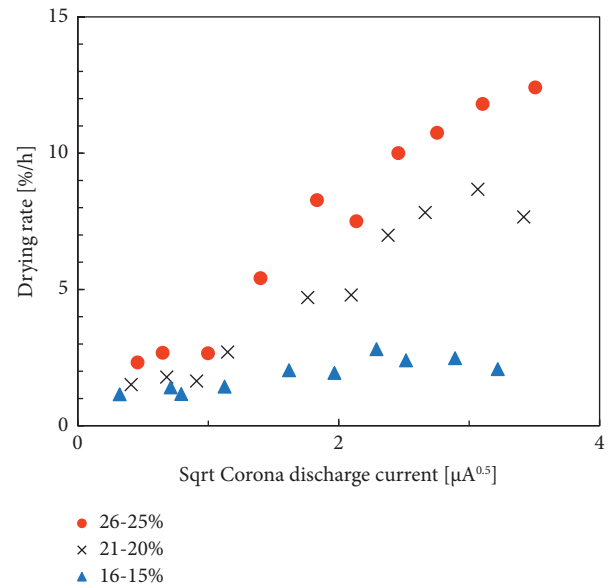


FIGURE 2: Plot of the drying rate against the sqrt of corona discharge current in each moisture content zone.

moisture content zone. The results support the fact that the energy required for drying increases with low moisture content and that evaporation of internal moisture is the main factor in the late stage of drying.

The smaller the corona discharge current, the higher the energy efficiency for promoting the drying rate. This result suggests that the minimum corona discharge current that can satisfy the desired drying rate is the optimal corona discharge current value in terms of energy efficiency because the increase in the drying rate becomes slower as the corona discharge current increases.

The result (cf. Figure 2) shows that the drying rate depends on the moisture content zones of the target objects under the same corona discharge current. The results also clearly show that the energy efficiency is higher when the corona discharge current is smaller. This means that maximizing the total corona discharge current might not be the best strategy for developing the EHD drying in low-energy contexts, such as those in developing countries having high humidity environments. The results might differ depending on the target materials. Future research should investigate the energy efficiency of other target materials.

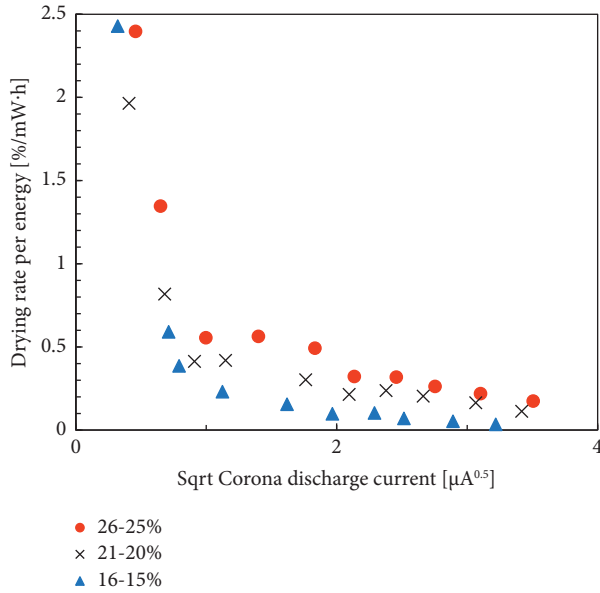


FIGURE 3: Plot of the drying rate per unit power against the qrt of corona discharge current in each moisture content zone.

### 3.2. Comparison between EHD Drying and Sun Drying.

Figure 4 shows the change in moisture content over time in the EHD drying experiment conducted under conditions simulating the Indonesian environment. When the applied voltage was 5 kV, the average value of the corona discharge current was  $2.81 \mu\text{A}$ . During the experiment, the drying rate at a low moisture content (16%~15%) was 1.17%/h, which was within the drying rate range of 0.1%~0.3%/h to prevent cracking.

Figure 4 shows that EHD drying under the Indonesian environment took about 6.2 hours for drying of 25%~15% moisture content. Under the conditions of 70% RH, the drying rate in the low moisture content zone (16%~15%) reached a range of 0.8%~1.3%, which was suppressed to prevent rice cracking, indicating that the drying rate was sufficient for practical use.

Table 1 shows the results of the comparison of the drying rate between the EHD drying experiment under the conditions that mimic the Indonesian environment and the sun drying experiment in Indonesia. The average drying rate in EHD drying was between 25% and 15% moisture content. The maximum drying rate was between 26% and 25%, and the minimum drying rate was between 16% and 15%.

Table 1 shows that the drying rate of EHD could maintain a high degree of dryness, while that of sun drying varied greatly depending on the time of day. The distribution of drying speeds reflects the difference, owing to the time period. A previous study reported that the drying speed is rapid in the morning and slow in the afternoon [18]. The energy required to dry 1 kg of water was 239 kJ/kg in the EHD drying under Indonesian environmental conditions when the evaluation range was a moisture content of 22%~15%. Table 2 shows a summary of the results of experiments in which the energy consumption for drying was measured

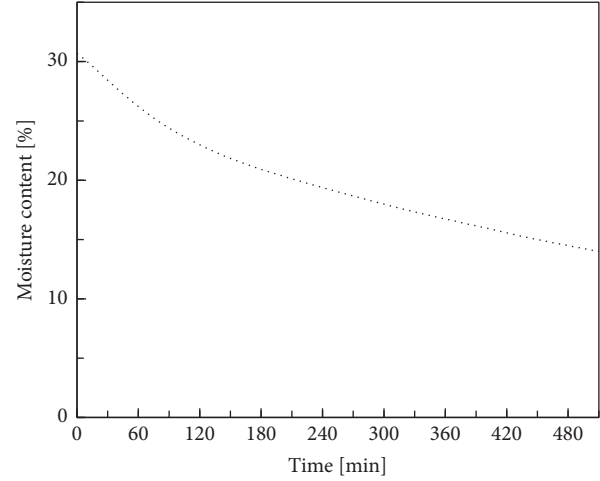


FIGURE 4: Plot of the moisture content change in the electrohydrodynamic (EHD) drying experiments under simulated Indonesian conditions (every 10 min).

TABLE 1: Comparison of drying rate between electrohydrodynamic (EHD) drying and sun drying.

	Drying rate (%/h)		
	Average value	Max value	Min value
EHD drying	1.62	3.83 (26%~25%)	1.17 (16%~15%)
Sun drying [18]	0.73	1.20	0.30

using commercially available products [27, 28]. Table 2 shows that the average energy required to dry 1 kg of water is 4,531 kJ/kg water on average. These results indicate that the EHD drying might be able to accelerate the drying process with approximately 1/20 of the energy of the grain dryer while achieving the same drying rate as that of the grain dryer.

Drying experiments were conducted under the condition that a sample of 10 g was accumulated on a 100 mm square ground electrode. The current density enables a 1 kg sample to accumulate on a 1 m square when the EHD system is simply extended horizontally. Even assuming that the EHD device can be stacked at a height of 50 mm without gaps, the processing capacity will be limited to 80 kg within a square of 1 m width, 2 m depth, and 2 m height. Considering that a small grain dryer, for example, KDR9N-SA, Kubota Corporation, Japan [29], has the capacity of drying 300~900 kg of grain, the current laboratory-level EHD device can process only 9% to 27% of the grain of a similar size grain dryer. Although there is a decrease in energy efficiency in industrialization, the comparison implies that the current EHD device is inferior to the grain dryer in terms of processing capacity. This suggests that there is room for investigating ways to increase the density of grains, such as appropriate electrode configurations, to increase the capacity of the EHD dryer.

In contrast to sun-drying, 2~4 cm of accumulation is assumed because sun drying occurs through solar radiation

TABLE 2: Energy required for a grain dryer to dehydrate 1 kg of water.

Research	Target	Drying method	Energy required to evaporate water (kJ/kg water)
Durance and Wang [27]	Tomato	Air drying	29,900
Durance and Wang [27]	Tomato	Vacuum microwave drying	8600
Billiris et al. [28]	Rice	Hot wind	4,531 (average of eight trials)

[25]. Given that the EHD dryer can accelerate the drying process even with accumulation, EHD drying is a technology that can fully replace sun drying in terms of processing volume.

#### 4. Conclusion

In this study, we examined whether the grain drying method using EHD drying technology could be used for industrial application in agricultural sites of developing countries having high humidity environments where the energy efficiency of drying is important from the viewpoint of power supply. We experimented with the drying rate and its energy efficiency with respect to the corona discharge current value and confirmed that the dry rate increased, and the energy efficiency decreased as the corona discharge current increased. The results also show that the drying rate varies depending on the moisture content zones of the target objects. The results suggest that the dominant parameters for promoting EHD drying are the corona discharge current and moisture content zones of the target objects. As an example of a developing country, the experiment was conducted under conditions assuming the environment of Indonesia. It was confirmed that EHD drying could maintain a high dry lapse rate in a stable manner, as opposed to sun drying, where the dry rate varies by nearly four times depending on the time of day. In addition, it was confirmed that drying could be promoted with approximately 5% of the energy while exhibiting the same lapse rate as that of the grain dryer using both hot air and far-infrared rays. It was clarified that the EHD drying technology is effective for developing countries having high humidity environments with energy problems from the viewpoint of low energy consumption as a technology to replace the conventional drying process.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Additional Points

**Practical Application.** Drying is an effective way to store foods such as grains. However, drying by heat requires high energy, and drying by sunlight is highly influenced by the environment. This study examined whether the grain drying method using electrohydrodynamic (EHD) drying technology could be used for industrial application in agricultural sites of developing countries having high humidity environments where the energy efficiency of drying is

important from the viewpoint of power supply. It was confirmed that the EHD drying could maintain a high dry lapse rate in a stable manner, as opposed to sun drying, where the dry rate varies by nearly four times, depending on the time of day. The result implies that the EHD drying technology may become an effective approach for developing countries having high humidity environments with energy problems, from the viewpoint of low energy consumption, as a technology to replace the conventional drying process.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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