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## Article

# Is Non-Thermal Plasma Treatment of Commodity Lettuce Seeds Worth It? Economic Impacts and Yield of Lettuce in Indoor Vertical Farming Testing Dry Air, Wet Air, N<sub>2</sub> and O<sub>2</sub> Plasmas

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## Abstract

Agricultural seeds are sold as commodities yet seed quality can be non-uniform. Despite extensive literature plasma treatments of seeds providing advantages for many crops, lettuce studies are limited. This study provides a systematic investigation of the impacts of non-thermal plasma treatments with various feed gases (N<sub>2</sub>, O<sub>2</sub>, dry air, and wet air) on the germination and growth characteristics of four lettuce cultivars (Red Oakleaf, Black Simpson, Valley Heart Romaine, and Paris Romaine) under controlled cultivation conditions in an agrivoltaic agrotunnel. Results show a complex interaction between germination time, rate and yield across the different cultivars and plasma treatments. The energy consumption of plasma treatments was negligible for all treatments, while labor costs for small-batches of seeds accounted for the largest share of secondary operating costs. Despite additional expenses, including labor, O&M, and degradation costs, the reduced seed requirements from higher germination rates and higher yield increase net profit by 12.0% compared to non-treated cultivation in the most impacted (Valley Heart Romaine) lettuce. There is an opportunity for further cost optimization of the non-thermal plasma treatment for each type of lettuce seed, The results also indicate a need for a more granular view of lettuce seed commodity pricing.

**Keywords:** plasma treatment; NTP; cold plasma; controlled environmental agriculture; economics; power-to-food; food security; agrivoltaics; indoor farming; vertical farming; seeds

## 1. Introduction

Controlled environment agriculture (CEA), particularly indoor farming (IF) facilities have expanded because of increasing controllability on farming by providing high spatial efficiency [1], year-round production [1–3], low water use [2], low pesticide and herbicide use [4], etc. [5–8]. This in turn increase the labor and energy costs associated with the high-tech instrumentation and high level of production [9]. Agrivoltaics, by integrating the least-expensive [10] and easy-to-deploy renewable energy source [11], solar photovoltaics (PVs), into the agricultural farms [12,13], could offer a chance in mitigating the energy costs of CEA buildings operated at agricultural lands [14]. Agrivoltaic agrotunnels are the most aggressive example of PV-powered IF in practice that could address the energy costs by offering net-zero grid-connected CEA powered with a PV system with considerably low levelized cost of electricity (LCOE) [15]. Agrivoltaic agrotunnels as well as other IF systems studied in the literature have shown a good profit margin for high value crops such as herbs [7,16,17]. For other greens such as salads, however, they are also economically profitability at a lower rate [18]. This underscores the need for further investigations on cost optimizations and yield improvements

leading to higher profitability levels. One scientific approach would be to reduce the labor and consumable materials costs and increase the revenue by improving the quality of seeds.

Agricultural seeds are sold as commodities, but the quality of all seeds is not the same such that they need to be treated to increase the chance of their germination [19]. Conventional seed treatments often rely on costly or environmentally harmful chemicals, highlighting the need for more sustainable alternatives [20]. There are some cutting-edge techniques that can improve the seed quality by boosting the plant growth rate and the transformation of bioactive chemicals, protein, and peroxidase concentrations, as well as the decontamination of the seeds [21]. Plasma treatment, as one of the common methods is extensively studied in the literature [22]. Plasma treatment is an environmentally-friendly technology for agriculture [23], which addresses both bacterial and fungal plant diseases and boosts the yield, which accordingly contributes to higher revenue and higher food security levels [24]. The positive influences of plasma treatment were investigated on a wide range of crops including wheat [25,26], oat [27], lentil [28], rice [29], soybean [30], pea [31], rapeseed [32], radish [33], hemp [34], green chiretta [35], micro-greens [36], cucumber [37], and tomato [38]. Non-thermal plasma (NTP), also referred to as cold plasma, is a form of plasma that remains out of thermodynamic equilibrium and operates at temperatures near room temperature. It can be carefully controlled to avoid causing thermal damage to biological materials [39]. Plasma is an ionized gas generated under atmospheric or low-pressure conditions. NTP produces reactive species, electromagnetic fields, and UV radiation that alter seed molecules. Common plasma devices in agriculture include dielectric barrier discharge (DBD), microwave, corona, gliding arc, plasma jet, and radiofrequency-based plasma systems [40]. Typical feed gases include nitrogen ( $N_2$ ), oxygen ( $O_2$ ), dry/wet air, noble gases, reactive gases, hydrocarbons, and gas mixtures [40]. The biologic effects of NTP on various type of commodity seeds, particularly the ones used for traditional farming have been extensively evaluated [39–41]. Although there are a few research pieces on the positive impact of NTP activated water or nutrient solution and root-applied NTP treatments on the growth metrics (including yield [42–45], leaf area [43,44], leaf count [46], germination rate [43], chlorophyll content [43,47], and mineral uptake [44,48]) of CEA cultivation of leafy greens, particularly lettuce, the studies on the direct commodity seed treatments are scarce. One study showed the effectiveness of the direct seed treatments of mung bean, mustard and radish was higher than that of the indirect nutrient water treatments [20]. Three gas types of air,  $N_2$ , and  $O_2$  were utilized in this non-thermal DBD plasma treatment study. For all three gas types, the germination probability of mung bean, mustard and radish was significantly improved after seed treatment. In another study on aeroponic cultivation of two lettuce varieties (Perl Gem and Cervanek), seeds were treated with low-pressure air or DBD plasmas [49]. Although seed treatments influenced germination and early growth, they had no significant effect on biomass accumulation or the head-to-root ratio in either lettuce cultivars.

Despite the extensively proven advantages of direct and indirect plasma treatments on the growth indicators of a vast majority of crops in the literature, the research results on lettuce are very limited, thereby inconclusive. No significant investigations were conducted on different methods and gas type influences on commodity lettuce seeds. Although other power-to-x applications of plasma are elaborated in the literature [50], practical power-to-food potentials of plasma for indoor cultivation considering the real conditions and additional costs are not investigated. To fill this research gap, in this study four different lettuce seeds including Red Oakleaf, Black Simpson, Valley Heart Romaine, and Paris Romaine are treated under NTP of  $N_2$ ,  $O_2$ , dry air, and wet air feed gases. The treated and untreated (control) seeds are cultivated in a real full-scale vertical farming facility in an agrotunnel. To determine if it is worthwhile using excess electricity and/or labor to enhance the yield of indoor lettuce crops, the economic trade-off analysis between the revenue improvements and cost increments due to the secondary operating expenditures of plasma reactor on agrivoltaic agrotunnel is carried out.

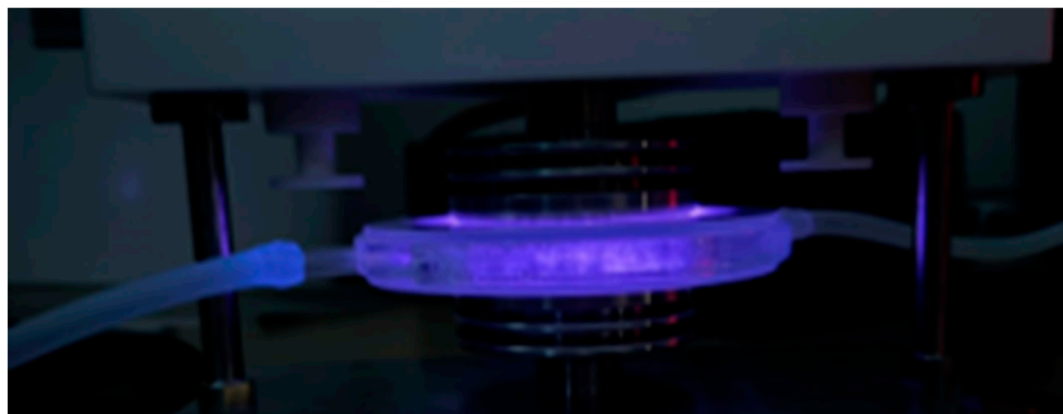
## 2. Materials and Methods

The whole research procedure is elaborated in two sections. First, the details of NTP treatments and cultivation experiments are detailed. Finally, the cost and energy analysis methodology is provided.

### 2.1. Non-Thermal Plasma Experiments

The non-thermal plasma system for seed treatment was operated at room temperature and atmospheric pressure within a disk-type non-thermal plasma reactor (Nanjing Suman Electronics Co., Ltd., China). As shown in Figure 1, the quartz disk-type reactor, with an outer diameter of 95 mm and an inner diameter of 60 mm, was positioned between the high-voltage and grounded electrodes. The effective discharge zone covered an area of 28.26 cm<sup>2</sup> with a gap of 8 mm. For all seed types, the same treatment conditions were applied: 25 seeds were treated with plasma for 2 min in the quartz disk-type reactor under a power density of 1.9 W.cm<sup>-2</sup> (Input voltage of 30 V and an input current of 2.4 A). The discharge was driven by a 9.0 kHz sinusoidal AC power source with an RMS voltage of 8.5 kV. Different working gases were employed for plasma-assisted seed treatment, including N<sub>2</sub>, O<sub>2</sub>, and dry air, each introduced at a flow rate of 20 mL min<sup>-1</sup>. Wet air with 3.3% water content was obtained by passing dry air through a water bubbler installed upstream of the plasma reactor.

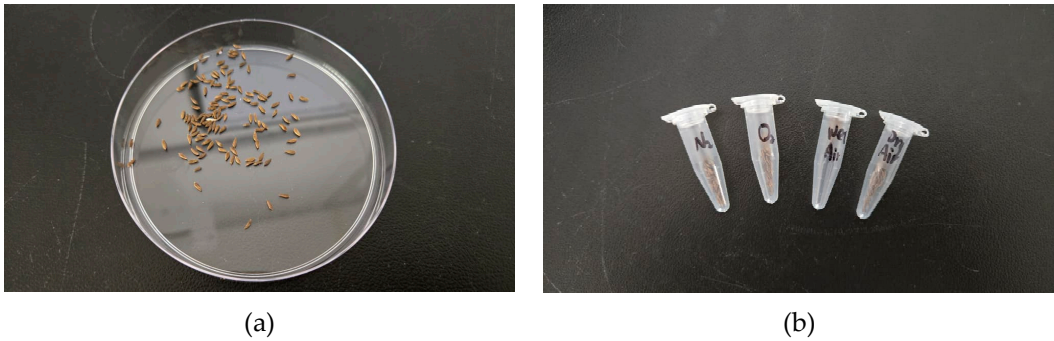
After plasma treatment, the seeds were sown immediately, since the surface activation induced by reactive species is transient. Prolonged storage leads to hydrophobic recovery of the seed coat and diminishes the enhanced water uptake capacity [26,49,51]. Moreover, the plasma-triggered biochemical signaling and enzymatic activities are short-lived, and excessive storage may even result in the accumulation of unfavorable oxidative by-products, thereby reducing the treatment benefits [30].



**Figure 1.** Experimental setup of the disk-type non-thermal plasma reactor for seed treatment.

Four cultivars, all in lettuce family, were selected to be tested. Red Oakleaf (RO), Black Simpson (BS), Valley Heart Romaine (VHR), and Paris Romaine (PR) were the tested seeds. Figure 2 presents the treated and non-treated Black Simpson seeds in vial tubes and sterile dishes. There is no visible difference between them. They were planted in different groups of single to multiple seeds per pot. Both treated and non-treated seeds were planted in peat pots by the usual hydroponic substrate used in agrotunnels, a 70/30 mix of coco coir and perlite [52], to study their performance under real conditions.

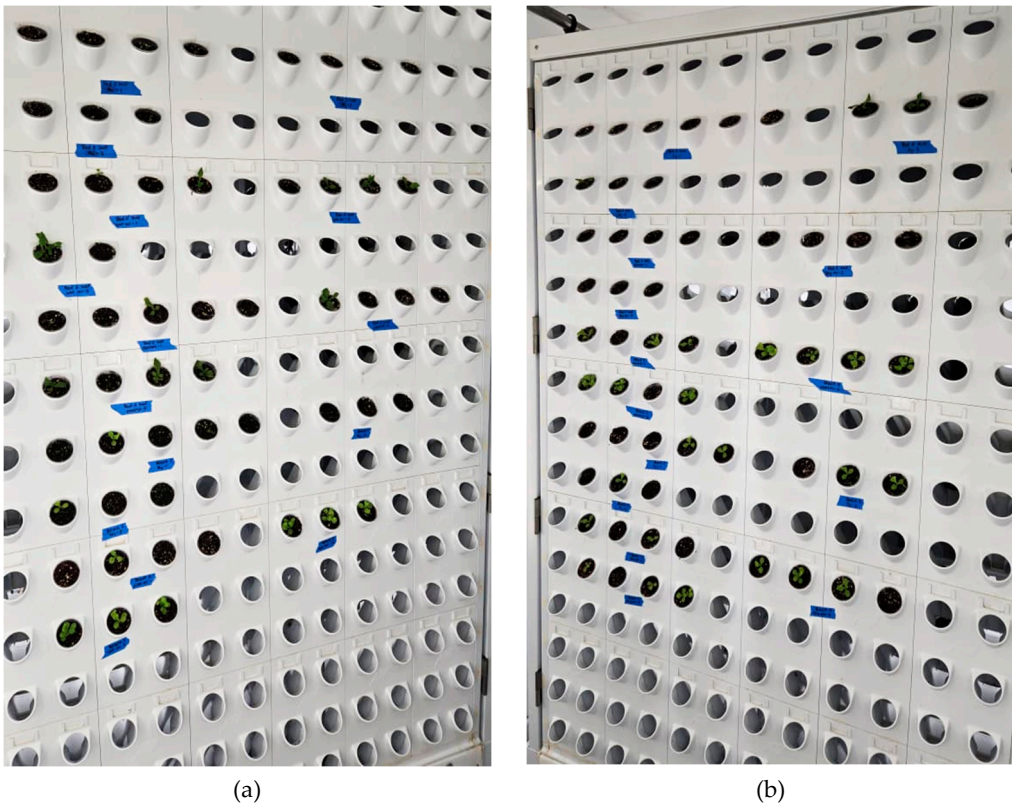
The planted pots were placed on true vertical hydroponic-aeroponic walls [53] in the agrivoltaic agrotunnel, Ilderton, ON [15]. Figure 3 shows the layout of the vertical grow walls in the main grow room of the agrotunnel. The germinated pots were placed on the ports on these vertical walls, as shown in Figure 4.

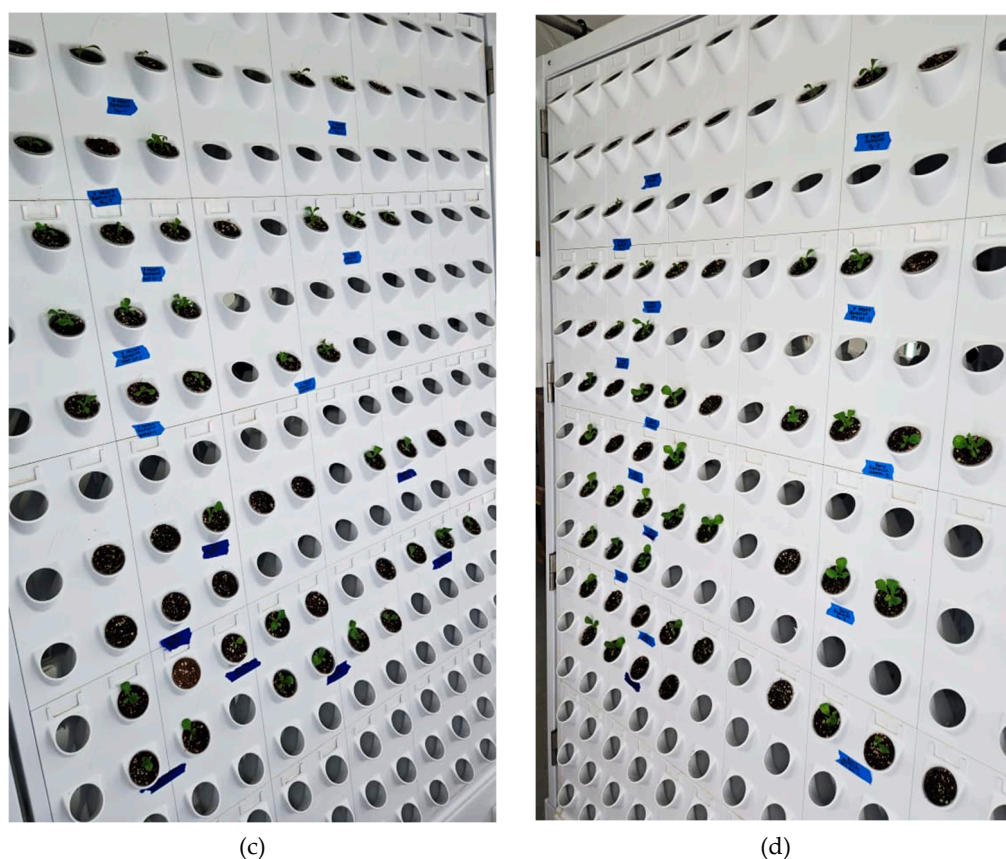


**Figure 2.** The picture of Black Simpson lettuce seed samples: (a) non-treated seeds in sterile dish, (b) treated seeds in vial tubes.



**Figure 3.** An agrivoltaic agrotunnel with 8 grow walls used in the study [18].





**Figure 4.** The germinated cultivars placed on the grow walls: (a) RO and BS on side 1-door 1, (b) RO and BS on side 1-door 2, (c) VHR and PR on side 2-door 1, (d) VHR and PR on side 2-door 2.

All seeds were treated identically in identical environmentally controlled conditions. The cups were irrigated by nutrient water, whose pH level was balanced within the range of 6.0-7.0 and the electrical conductivity was maintained between 1.5 and 2.0 mS/cm. The watering cycle was 2 times per day with a 2-minute duration. The grow room was kept at a temperature of between 22 and 23 °C with a relative humidity ranging from 50% to 55%.

## 2.2. Energy and Economic Trade-off Analysis

Three main growth metrics of germination rate ( $G$  in %), germination time ( $t_{\text{germination}}$  in days), and fresh biomass yield ( $Y'$  in kg/cultivation period) were measured and compared between four gas types for NTPs and the control plants. Cultivation period is defined as the time from planting to the last harvest in days. These three metrics were either directly or indirectly connected to the total number of required commodity seeds ( $N_{\text{annual}}$ ), annual yield ( $Y_{\text{annual}}$  in kg/year), annual energy required ( $E_{\text{annual}}$  in kWh/year) for plasma treatments, and total labor time dedicated to implementation of treatments ( $L_{\text{annual}}$  in h/year), all of which are the main economic drivers in the trade-off analysis. Figure 5 illustrates the estimation process of annual evaluating metrics (State 3 and 4) for the commercial MAX version of the agrotunnel (12,816 grow ports) based on the experimented data (State 1). State 2 represents the calculations per cultivation period. All the parameters are defined in Table 1.

Actual number of required seeds per cultivation period is calculated using Equation (1).

$$N = \frac{12,816}{G} \quad (1)$$

All annual parameters ( $P_{\text{annual}}$ ) will be estimated by extrapolating the equivalents calculated during the cultivation period ( $P_a$ ) to the whole year, as shown in Equation (2).

$$Pa_{annual} = Pa \times \frac{12}{C}$$

(2)

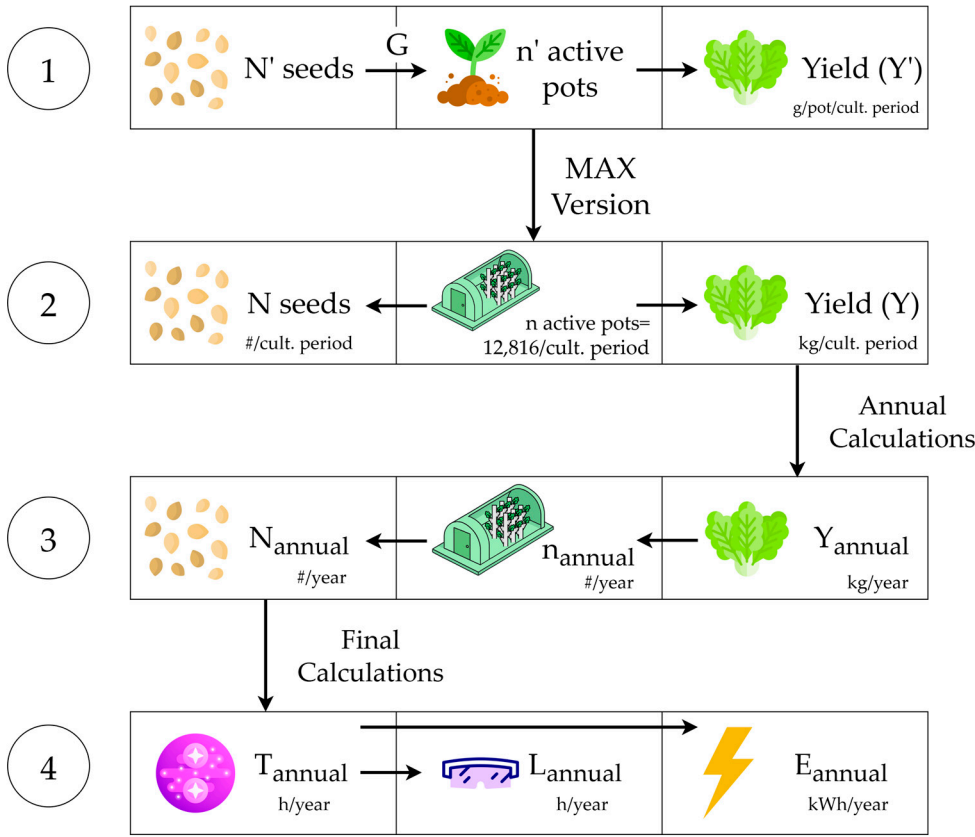


Figure 5. The annual cost and revenue estimation procedure for commercial MAX agrotunnel.

Table 1. Technoeconomic parameters definitions and units.

Parameter	Definition	Unit
N'	Total tested seeds	#
n'	Total tested pots	#
Y'	Average yield per pot	g/pot/cult. period
N	Actual number of required seeds per cult. period	#/cult. period
n	Total number of pots grown per cult. period	12,816/cult. period
Y	Average total yield per cult. period	kg/cult. period
N <sub>annual</sub>	Actual number of required seeds per year	#/year
n <sub>annual</sub>	Total number of pots grown per year	#/year
Y <sub>annual</sub>	Average total annual yield	kg/year
E <sub>annual</sub>	Total plasma treatment energy required per year	kWh/year
T <sub>annual</sub>	Total plasma treatment time required per year	h/year
L <sub>annual</sub>	Total plasma treatment labor time required per year	h/year
G	Germination rate	%
t <sub>germination</sub>	Germination time	days
C	Cultivation period	months
R <sub>annual</sub>	Annual revenue	USD\$/year
Pa	Parameter within the cultivation period	-
Pa <sub>annual</sub>	Annual parameter	-

\* The USD to CAD exchange rate is assumed to be 0.72 at the times of analysis [54].

Energy required for each type of plasma treatment is calculated using the fundamental electrical quantities measured for the current disk-type quartz plasma reactor provided in Table 2.

**Table 2.** Electrical parameters’ values for treatment of 25 seeds.

Parameter	Value	Unit
N’	25	#
Treatment time ( $t_{\text{treatment}}$ )	2	minute
Input voltage (V)	30	V
Input current (I)	2.4	A

To perform the economic analysis, several basic assumptions must be made, and the primary cost per unit values for key operating expenditures should be defined. First, the total number of required seeds per year provides the basis for calculating the annual seed cost, annual treatment labor time, and annual treatment energy, which is defined as the multiplication of the plasma reactor’s power rating ( $P_{NTP}$ ) and the annual treatment time ( $T_{\text{annual}}$ ), as shown in Equation (3). The energy cost for the case study in London, ON, expressed in \$/kWh, was obtained from the utility rates provided by London Hydro [55].

$$E_{\text{annual}} = P_{NTP} \times T_{\text{annual}} = \frac{V \cdot I}{1000} \cdot \frac{N_{\text{annual}}}{N'} \cdot t_{\text{treatment}} \times \frac{h}{60min}$$

(3)

The average cost of lettuce seeds was considered to be \$1.62 USD per 1,000 seeds [56–58]. On the other hand, the annual revenue ( $R_{\text{annual}}$  in USD\$/year) can be calculated using Equation (4). The average unit price of organic lettuce was assumed to be \$25.35 USD/kg [59].

$$R_{\text{annual}} = Pr_{\text{lettuce}} \times Y_{\text{annual}}$$

(4)

To prepare the reactor for each treatment cycle, the operator must perform several pretreatment tasks, such as removing the treated seeds, cleaning the reactor, and adding the next batch, which takes approximately 10 minutes per cycle. The minimum wage in Ontario, set at \$12.67 USD/h, was used as the unit labor cost [60]. The capital cost of the current lab-scale system, including the plasma generator and quartz reactor, with a total operating lifetime of 20,000 hours, is \$3,600 USD [61]. The average operation and maintenance (O&M) cost for similar devices is assumed to be 5% of the initial fixed cost [62]. The degradation cost of the equipment can be estimated based on the ratio of the annual treatment time to the total lifetime operating hours.

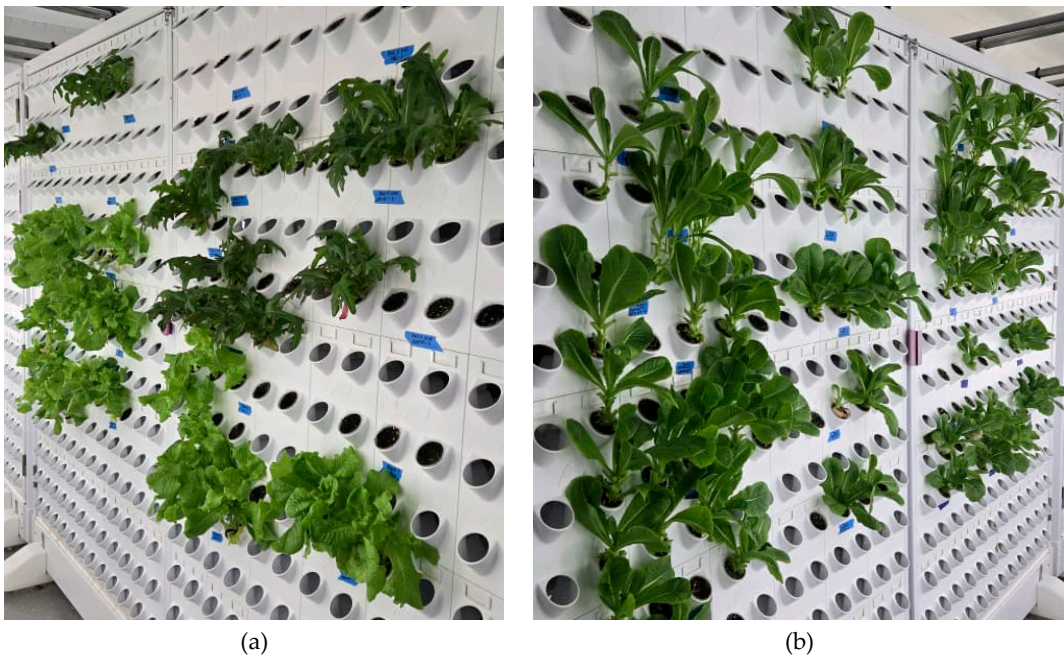
3. Results

In this section, the results of all measurement and calculation procedures defined in Figure 5 will be elaborated. The first phase of results will present experimental investigations of the cultivation processes. Figure 6 shows the mature lettuce plants on grow vertical walls in the agrotunnel, proving the success of cultivation and maintenance experiments. All varieties had a cultivation period (C) of two months.

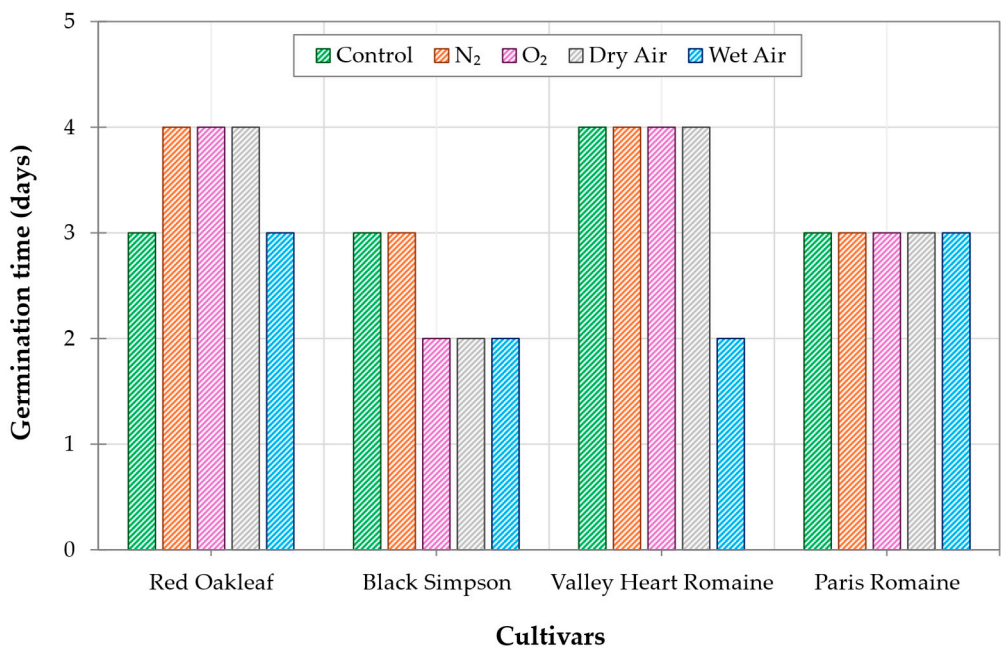
As the first parameter, the germination time was investigated. Figure 7 presents the germination time of different cultivars under various treatments and the control condition. According to the results, there is no significant difference in  $t_{\text{germination}}$  among the treatments. The main variation is attributed to the cultivar type. It should also be noted that the effect of  $t_{\text{germination}}$  will be indirectly examined through the yield and cultivation period of the plants. Therefore,  $t_{\text{germination}}$  is not considered a parameter to be evaluated independently.

Germination rate (G) is the first key parameter demonstrating the economic effectiveness of plasma treatments, both directly and indirectly. The average G of all treated and control seeds is reported in Table 4. As shown in Table 4, for the Red Oakleaf cultivar, the wet air treatment resulted in a germination rate of 50%, compared to 25% for the control seeds (100% improvement). Similarly, for the Black Simpson and Valley Heart Romaine varieties, the wet air treatment again achieved

higher G values (81.5% and 82.4%, respectively) compared to the control (63.9% and 69.4%, respectively). Paris Romaine seeds, however, showed a higher G (77.8%) under the O<sub>2</sub> treatment, followed by the control group with 65.8%.



**Figure 6.** The ready to harvest crops on the grow walls: (a) RO and BS on side 1, (b) VHR and PR on side 2.



**Figure 7.** Germination time ( $t_{\text{germination}}$ ) of seeds (control vs NTP treatments).

Successful treatments can be identified by evaluating the yield investigations shown by Figure 8. Wet Air treatment could have the most considerable impact generally, with the most significant achievement on VHR (51.7 vs. 42.5 g/pot/cult.period in control). Treatments of Red Oakleaf seeds were not effective according to the reported results. For Black Simpson, although dry air and wet air treatments could perform reasonably, the most significant influence resulted in N<sub>2</sub> treatment (54.2 vs 48.1 g/pot/cult.period in control). Ultimately, for Paris Romaine, O<sub>2</sub> treatment led to reasonably significant yield (58.4 g/pot/cult.period) compared to control (51.8 g/pot/cult.period).

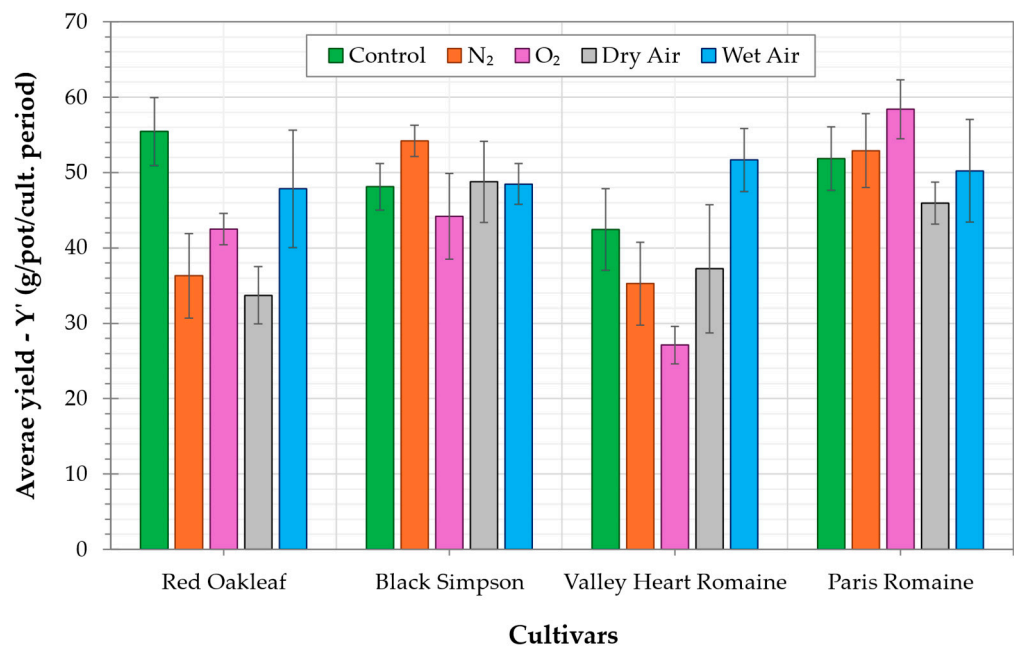
**Table 4.** Average germination rate of seeds (control vs NTP treatments).

Variety/treatment	Average germination rate (%)	Improvement compared to control (%)	Error (±%)
<b>Red Oakleaf</b>			
Control	25.0	-	0.0
N <sub>2</sub>	21.7	-13.3	2.9
O <sub>2</sub>	24.1	-3.7	8.5
Dry Air	26.7	6.7	2.9
Wet Air	50.0	100.0	0.0
<b>Black Simpson</b>			
Control	63.9	-	12.7
N <sub>2</sub>	61.1	-4.3	9.6
O <sub>2</sub>	35.6	-44.3	3.8
Dry Air	47.2	-26.1	4.8
Wet Air	81.5	27.5	17.0
<b>Valley Heart Romaine</b>			
Control	69.4	-	4.8
N <sub>2</sub>	58.3	-16.0	14.4
O <sub>2</sub>	30.6	-56.0	4.8
Dry Air	60.2	-13.3	13.1
Wet Air	82.4	18.7	7.0
<b>Paris Romaine</b>			
Control	65.8	-	19.4
N <sub>2</sub>	38.9	-40.9	9.6
O <sub>2</sub>	77.8	18.1	19.2
Dry Air	27.2	-58.6	11.8
Wet Air	53.3	-19.0	5.8

With the potential for growing organic products in the agrivoltaic agrotunnel [18], the selection of the BS, VHR, and PR cultivars can provide the key components of a spring mix or green mix lettuce pack [18]. Therefore, the application of three plasma treatments, N<sub>2</sub>, O<sub>2</sub>, and wet air, on the selected seeds was investigated, and an economic trade-off analysis considering the secondary costs was conducted.

The key parameters for the successful treatments, as presented in Table 5, were used for the cost analysis. The germination rate, annual yield, and annual seed requirements were all improved for the NTP-treated seeds of Romaine family compared to that in control. Despite the higher total yield for treated BS seeds, their germination rate was lower than control seeds, which led to more total seed requirements, and more treatment labor in turn. Among the Romaine varieties, VHR seed treatment caused a 21.7% yield improvement (3,973 vs 3,264 kg/year) compared to PR variety with 12.6% (4,491 vs 3,987 kg/year). The germination rate for VHR variety was also higher compared to PR, leading to reduced seed count (93,320 vs 98,838 per year), seed treatment time (124 vs 132 h/year), and labor hours (622 vs 659 h/year). Table 5 also reveals that the energy consumption of plasma treatments is small and negligible in cost analysis. In conclusion of the final annual calculations, the VHR variety can be identified as the most responsive to the NTP seed treatments. The cost–revenue

trade-off analysis is conducted in the following, comparing the wet air-treated seeds with the control seeds.



**Figure 8.** Average yield of cultivated crops (control vs NTP treatments). only including those that germinated.

**Table 5.** The average values of key defining parameters for the cost analysis of selected treatment-cultivars.

Parameter	BS		VHR		PR	
	Control	NTP	Control	NTP	Control	NTP
Treatment	-	N <sub>2</sub>	-	Wet Air	-	O <sub>2</sub>
G (%)	63.9%	61.1%	69.4%	82.4%	65.8%	77.8%
Y <sub>annual</sub> (kg/year)	3,700	4,168	3,264	3,973	3,987	4,491
N <sub>annual</sub> (seeds/year)	120,338	125,853	110,801	93,320	116,863	98,838
E <sub>annual</sub> (kWh/year)	0	12.1	0.0	9.0	0.0	9.5
L <sub>annual</sub> (h/year)	0	839	0	622	0	659
T <sub>annual</sub> (h/year)	0	168	0	124	0	132

Table 6 presents the final results of the cost and revenue analysis for the VHR-wet air treatment. The energy cost of the treatments was negligible because solar electricity generation was equal to 177,100 kWh/year [18] while the entire annual plasma treatment was only 9 kWh. On the other hand, the labor cost represents the largest contribution to the secondary operating expenditures of the NTP process (\$7,882 USD/year). Despite the additional secondary costs associated with the plasma treatments, especially labor, the reduced number of required seeds and the higher yield resulted in an overall 12.0% improvement in the net profit compared to the non-treated seed cultivation (\$92,481 vs. \$82,573 USD/year).

**Table 6.** Final cost-revenue trade-off analysis between the non-treated and plasma-treated seed cultivation in indoor vertical farming.

Parameter	Control	NTP
Selected cultivar-NTP	Valley Heart Romaine	VHR-Wet Air
Revenue (USD/year)	82,753	100,718
Seed cost (USD/year)	179	151
Labor cost (USD/year)	0	7,882

O&M cost (USD/year)	0	180
Degradation cost (USD/year)	0	24
Net profit (USD/year)	82,573	92,481
Net profit improvement (%)	-	12.0

4. Discussion

This article investigated the effect of non-thermal plasma treatments with different feed gases on the germination and growth metrics of different lettuce seeds in practical growing conditions of a vertical indoor farming facility (agrivoltaic agrotunnel). In addition, the economic viability of these practices was studied and compared by conducting the combined revenue-cost trade-off analysis. Four lettuce seeds of Red Oakleaf, Black Simpson, Valley Heart Romaine, and Paris Romaine were tested under four feed gases of N<sub>2</sub>, O<sub>2</sub>, dry air, and wet air. A quartz disk-type non-thermal plasma reactor was used with 30 V, 2.4 A, and 2 minutes duration of treatment.

Wet air treatment could generally expose better performance in germination rate (18.7-100% improvement) compared to the equivalent control plants, except for PR, whose germination rate was improved by 18.1% under O<sub>2</sub> treatment. Exposure to O<sub>2</sub> plasma can be attributed to the formation of O<sub>3</sub> and O· radicals, which may mildly oxidize seeds and enhance respiration rates [33]. However, for seed types with thin seed coats, the same 2-minute O<sub>2</sub> treatment may oxidize membrane proteins beyond the beneficial activation threshold, thereby inhibiting germination (as seen in Figure 8).

The total fresh weight production, however, was the most important factor in selecting the successful cultivar-treatment combinations. Except for RO, for which there was no significant positive improvement in production yield, wet air, could result in either neutral or significant positive yield increments for the treated cultivars. Unlike O<sub>2</sub>- or air-based plasmas, the N<sub>2</sub> discharge primarily generates reactive nitrogen species, including NO, NO<sub>2</sub>, and N<sub>2</sub>O. Element O may originate from residual gases within the reactor. The differing response of BS seeds compared to VHR and PR seeds attributable to their greater sensitivity to NO<sub>x</sub> in certain enzymes, which indicate an area of future work. Thus, except for the N<sub>2</sub>-treated BS seeds, which could produce 12.6% more fresh weight but accompanied by a decreased germination rate of 4.3%, both total yield and germination rate of Romaine seeds (VHR and PR) were positively responsive to the wet air and O<sub>2</sub> treatments, respectively. The contrasting results between dry- and wet-air plasma treatments can be attributed to the different reaction pathways induced by the presence of water vapor. In dry air, the discharge predominantly produces O· and O<sub>3</sub>, which impose strong oxidative stress on the seed coat, leading to surface hardening and limited water permeability. Conversely, introducing a small fraction of water vapor suppresses O<sub>3</sub> formation while enabling OH· and H<sub>2</sub>O<sub>2</sub> generation through O-H<sub>2</sub>O reactions. These species cause mild oxidation and introduce polar oxygen-containing groups on the cuticular surface, enhancing water imbibition and germination [39]. VHR-wet air with 21.7% total yield improvements and 18.7% higher germination rate compared to control, was selected to develop further revenue-cost analyses on the NTP process integrated into the IF system. The observation of somewhat different results among various plant cultivar, as similarly observed in the literature [26,27,34,35,49], may be attributed to several factors, including seed or plant genetics, contamination, insufficient plasma processing energy or duration, etc.

This study also revealed that using the current quartz disk-type reactor for a 112 m<sup>2</sup> indoor farming facility with 76,896 active ports for a year-round production, would impose a negligible amount of electricity load (9 kWh/year) on the system with a total solar generation of 177,100 kWh/year. Since the current plasma device can only treat a batch of 25 seeds at a time, the operation of this reactor demands for a considerable amount of time, thereby contributing a notable labor cost (44% of total raised revenue due to the wet air treatment of VHR seeds). Although the positive effects of wet air treatment on germination rate and total yield led to an overall 12.0% increase in net profit compared to non-treated seed cultivation, despite the additional labor, O&M, and degradation costs associated with operating NTP reactors, there is a need for future studies to explore alternative commercial- or industrial-scale systems with higher treatment capacities. In addition, there is a

significant opportunity to reduce labor costs using an automated system to load and unload seeds for pre- and post-treatment processes. Future research is also needed to investigate the effects of NTP on a wider range of lettuce seed varieties obtained from the same vendors and replicate the experiments multiple times to improve the reliability of the results. Moreover, examining the influence of voltage and treatment duration on seed decontamination and growth enhancement could help further achievements in the techno-economic optimization of the process.

## 5. Conclusions

This research determined how non-thermal plasma treatments with various feed gases (N<sub>2</sub>, O<sub>2</sub>, dry air, and wet air) influence the germination and growth characteristics of different lettuce cultivars (Red Oakleaf, Black Simpson, Valley Heart Romaine, and Paris Romaine) under real cultivation conditions in an agrivoltaic agrotunnel. Furthermore, the study assesses the economic feasibility of these treatments through a comprehensive revenue–cost trade-off analysis. Experiments were conducted involving continuous harvesting cycles on mature plants during a cultivation period of two months. The germination time of seeds (treated and control) was varying within a range of 2–4 days. The germination time, however, had an indirect impact on the growth performance of the plants during their lifespan.

Except for treated PR seeds with 77.8% germination rate vs control of 65.8%, wet air plasma treatment could result in higher germination rates (18.7–100% improvement) compared to control (non-treated) seeds. This factor directly indicates the total required seeds for operation of commercial MAX agrotunnel with 12,816 active ports.

In yield analysis, the wet air treatment showed the greatest impact, particularly for the VHR variety (51.7 vs. 42.5 g/pot/cultivation period in the control). The treatments had no notable effect on RO, however. For BS, the N<sub>2</sub> treatment yielded the highest improvement (54.2 vs. 48.1 g/pot/cultivation period), while for PR, the O<sub>2</sub> treatment led to a significant increase (58.4 vs. 51.8 g/pot/cultivation period). Hence, BS, VHR, and RO were selected to conduct further cost-revenue analysis.

Although treated BS seeds produced a higher total yield, their lower germination rate increased the required seed quantity and treatment labor time. Among the Romaine cultivars, VHR showed the best response to NTP treatment, with a 21.7% yield improvement (3,973 vs. 3,264 kg/year) compared to PR's 12.6% (4,491 vs. 3,987 kg/year). The higher germination rate of VHR also reduced annual seed requirements (93,320 vs. 98,838), treatment time (124 vs. 132 h), and labor hours (622 vs. 659 h). Accordingly, the VHR variety demonstrated the greatest response to NTP treatment with wet air feed gas. The energy consumption of plasma treatments was negligible for all treatments and cultivar types. In contrast, labor costs (\$7,882 USD/year) accounted for the largest share of secondary operating costs in the NTP process. Despite these additional expenses, including labor, O&M, and degradation costs, the reduced seed requirements and higher yield led to a 12.0% increase in net profit compared to non-treated cultivation (\$92,481 vs. \$82,573 USD/year).

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Abbreviations

The following abbreviations are used in this manuscript:

CEA	Controlled environment agriculture
IF	Indoor farming
PV	Photovoltaics
LCOE	Levelized cost of electricity
NTP	Non-thermal plasma
RO	Red Oakleaf
BS	Black Simpson
VHR	Valley Heart Romaine
PR	Paris Romaine

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