

# Greenhouse and Nursery Producers Have Optimistic Outlook Toward Adoption of Plasma-activated Water in Young Plant Production

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**KEYWORDS.** cold plasma, controlled environment agriculture, seed germination, seedling growth, survey

**ABSTRACT.** Cold atmospheric plasma applied to water results in a multitude of direct and indirect chemical reactions at the interface, generating a solution referred to as plasma-activated water (PAW), which is rich in reactive nitrogen and oxygen species and has been shown to enhance several processes important to seed germination and seedling production. More specifically, a growing body of research supports the role of PAW in augmenting the seed germination rate and uniformity. Additionally, PAW has been shown to enhance growth and vigor of crop seedlings. In 2023, a survey was launched to ascertain information about the current knowledge of and interest in this technology and, upon discovery, gauge plant producers' willingness to learn about and adopt PAW in their own operations. Responses from young plant producers were collected between Aug 2023 and Mar 2024 using an anonymous survey. Of the 82 respondents, only 18% were aware of PAW. Despite its obscurity, 78% indicated that they were interested in learning more about PAW and 55% were in favor of trying PAW in their cultural practices. Farmers growing in larger production areas, using indoor vertical farms, or producing herb crops were among the most inclined to learn about and try PAW to enhance their production. Additionally, the frequency with which farmers have experienced poor seed germination positively correlated with overall willingness to try PAW.

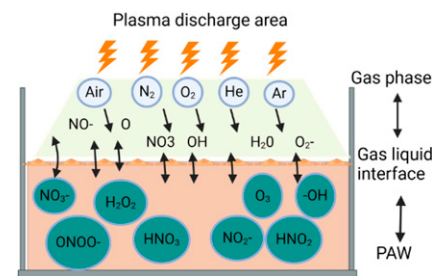
Plasma is created by adding energy (heat or an electrical charge) to an object (liquid or solid) or a neutral gas, thus causing electron separation from atoms or molecules.

Intrinsically, plasma comprises ionized gases consisting of positive and negative ions, excited and neutral atoms, free radicals, ground and excited state molecules, and ultraviolet photons (Bogaerts et al. 2002; Thirumdas et al. 2018). Plasmas can be categorized into high-temperature or fusion (thermal, hot) plasma and low-temperature or gas discharge (non-thermal, cold) plasma based on their thermal equilibrium (Bogaerts et al. 2002). The latter, cold plasma, can be used to dissolve ionized gas in water to create what is known as plasma-activated water (PAW). Cold plasma in an open atmosphere is applied above or below the surface of water, thus triggering proliferation of chemical reactions at the interface between the gas and liquid phases generating reactive species in solution (Fig. 1) (Gao et al. 2022).

The constituents of PAW, electricity, water, and gases, namely atmosphere, are considered benign and natural in derivation. The resulting PAW produced after direct exposure

to plasma primarily consists of the following dissolved reactive oxygen and nitrogen species (RONS): O, O<sup>•</sup>, ozone (O<sub>3</sub>), OH<sup>•</sup>, OH<sup>•</sup>, N, NO, NO<sub>2</sub>, NO<sub>2</sub><sup>•</sup>, and NO<sub>3</sub><sup>•</sup>, among others (Nijdam et al. 2012; Zhou et al. 2020). Many of these reactive species are known to affect cellular metabolism in biological systems (Kaushik et al. 2018; Laroque et al. 2022). Research of direct applications to biological tissues, such as human bodies, plants, and foods, has gained considerable traction in recent years (Ito et al. 2018; Kaushik et al. 2018; Laroque et al. 2022; Leandro et al. 2024; Savi et al. 2025).

Entrepreneurs have developed economically feasible methods of producing PAW, which has led to a multitude of research opportunities centered on plant production known as plasma agriculture (Puač et al. 2018). PAW is a virtual “Swiss Army knife” in terms of its agricultural usefulness. It exhibits several promising applications that influence the plant life cycle by enhancing seed germination, stimulating plant growth, increasing tolerance to plant stressors, reducing soil-borne pathogens, and boosting natural plant defenses and fertilizer production (Gao et al. 2022; Herianto et al. 2021; Park et al. 2013; Savi et al. 2025; Sivachandiran and Khacef 2017). As an antimicrobial, PAW can be used to disinfect preharvest and postharvest surfaces (Lukes et al. 2014; Wang and Salvi 2021). Moreover, widespread use of PAW can alleviate toxicological effects on



**Fig. 1. Schematic diagram of a cold atmospheric plasma discharge area and plasma-activated water (PAW) formation. The synthesis of PAW is preceded by electrical discharge in the gas phase (air or other mixtures of gases) under or above a volume of water, thereby creating a gas-liquid interface through which positive and negative ions are transmitted to water, resulting in the formation of reactive oxygen and nitrogen species.**

Received for publication 29 May 2025. Accepted for publication 24 Jul 2025.

Published online 29 Aug 2025.

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<https://doi.org/10.21273/HORTTECH05689-25>

**Table 1. Summary statistics and definitions of variables used in the analysis based on the survey data of 82 US growers.**

| Variable                                  | Definition                                                                                                                                                                                                                 | Mean  | SD    |
|-------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|
| Willing to learn about PAW                | 1 if participants are willing to learn about PAW; 0 otherwise                                                                                                                                                              | 0.780 | 0.416 |
| Willing to participate in trials with PAW | 1 if participants are willing to participate in trials with PAW; 0 otherwise                                                                                                                                               | 0.548 | 0.501 |
| Area                                      | Approximate production area of participants greenhouse/nursery (in acres)                                                                                                                                                  | 2.676 | 3.108 |
| Indicators of growing environments        |                                                                                                                                                                                                                            |       |       |
| Greenhouse                                | 1 if participants use greenhouse; 0 otherwise                                                                                                                                                                              | 0.780 | 0.416 |
| High tunnel                               | 1 if participants use high tunnel; 0 otherwise                                                                                                                                                                             | 0.146 | 0.356 |
| Outdoor container nursery                 | 1 if participants use outdoor container nursery; 0, otherwise                                                                                                                                                              | 0.305 | 0.463 |
| Indoor vertical farm                      | 1 if participants use indoor vertical farm; 0 otherwise                                                                                                                                                                    | 0.171 | 0.379 |
| Indicators of crop types                  |                                                                                                                                                                                                                            |       |       |
| Berries                                   | 1 if participants plant berries; 0 otherwise                                                                                                                                                                               | 0.085 | 0.281 |
| Herbs                                     | 1 if participants plant herbs; 0 otherwise                                                                                                                                                                                 | 0.256 | 0.439 |
| Floriculture/ornamental crops             | 1 if participants plant floriculture or ornamental crops; 0 otherwise                                                                                                                                                      | 0.598 | 0.493 |
| Vegetables for production                 | 1 if participants plant vegetables for production; 0 otherwise                                                                                                                                                             | 0.329 | 0.473 |
| Vegetables for transplants                | 1 if participants plant vegetables for transplants; 0 otherwise                                                                                                                                                            | 0.329 | 0.473 |
| Young plants                              | 1 if participants plant young plants; 0 otherwise.                                                                                                                                                                         | 0.317 | 0.468 |
| Other plants                              | 1 if participants plant other plants; 0 otherwise                                                                                                                                                                          | 0.146 | 0.356 |
| Indicators of production methods          |                                                                                                                                                                                                                            |       |       |
| Conventional production methods           | 1 if participants use conventional production methods; 0 otherwise                                                                                                                                                         | 0.829 | 0.379 |
| Organic production methods                | 1 if participants use organic production methods; 0 otherwise                                                                                                                                                              | 0.402 | 0.493 |
| Indicators of seed and seedling           |                                                                                                                                                                                                                            |       |       |
| Using seed                                | 1 if participants use seed; 0 otherwise                                                                                                                                                                                    | 0.817 | 0.389 |
| Using seedling                            | 1 if participants use seedling; 0 otherwise                                                                                                                                                                                | 0.732 | 0.446 |
| Aware the function of PAW                 | 1 if participants are aware of the function of PAW; 0 otherwise                                                                                                                                                            | 0.183 | 0.389 |
| Lower germination frequency               | Frequency of obtaining lower germination than the labeled germination rate on seed packages among participants using seeds: 1 = never, 2 = sometimes, 3 = approximately half of the time, 4 = most of the time, 5 = always | 2.284 | 1.086 |
| Preplanting seed treatments               | Frequency of conducting preplanting seed treatments among participants using seeds: 1 = never, 2 = sometimes, 3 = approximately half of the time, 4 = most of time, 5 = always among                                       | 1.791 | 0.978 |
| Poor seedling growth                      | Frequency of encountering inconsistent/poor seedling growth among participants using seedlings: 1 = never, 2 = sometimes, 3 = approximately half of the time, 4 = most of time, 5 = always                                 | 2.217 | 0.666 |
| Treatments to improve seedling growth     | Frequency of using treatments to improve seedling growth among participants using seedlings: 1 = never, 2 = sometimes, 3 = approximately half of the time, 4 = most of time, 5 = always                                    | 2.433 | 1.170 |

SD = standard deviation.

local ecosystems when used as an alternative to traditional agrichemicals (Gao et al. 2022; Puač et al. 2018). Therefore, PAW technology presents a unique opportunity in which agriculturalists can augment indoor crop production and significantly reduce synthetic chemical reliance; however, its adoption among industry professionals is scarce worldwide.

Worthwhile agricultural innovations not only enhance crop yields but also improve the welfare of farmers

and the economics of the food sector (Chavas and Nauges 2020). An increasing world population beckons for innovation in agriculture to meet the food demands of today and the coming years. Yet, the degree of perceived benefits of each innovation changes on an individual or farm basis (Sunding and Zilberman 2001). For farmers, the uncertainty of adopting a new technology increases risk in the form of capital and time. Disrupting the existing state

of affairs places operational profitability in limbo. Thus, it is paramount that operational decision-makers perceive an innovation as providing a positive net benefit before adoption. Essential criteria used by agricultural decision-makers to evaluate new technologies designed to improve their growing system are impacts on yield, costs, product quality, public health, and the environment (Sunding and Zilberman 2001).

Adoption of modern technologies in agriculture is considered fundamental to improving productivity (Takahashi et al. 2019), but distinguishing between a willingness to try such technologies and their sustained adoption is crucial for understanding their true impact. Before a farm can evaluate a new technology, the operator must first discover the innovation and then assess it based on the information available. As previously noted, PAW is not new, but its acclaim has been steadily growing among the scientific community. Progress has been made to expand industry awareness of PAW, albeit rather slowly. The objective of this survey was to provide a better understanding of greenhouse and nursery producers' knowledge of and willingness to try PAW in agricultural applications relative to the type and size of their respective operations as well as individual challenges encountered in young plant production. Because there is a small contingency of farmers who have adopted PAW technology in their cultural practices as well as a few startup companies that cater to these growers, the authors were motivated to prepare this survey. To the authors' knowledge, this is the first PAW survey conducted in the agricultural sector. This survey of growers was analyzed to assess factors that contribute to an individual's willingness to explore the potential benefits that PAW could have for their operation.

## Materials and methods

We conducted a survey to investigate farmers' understanding of the application of PAW on young plant production. Our online survey was implemented via online survey tool software (Qualtrics Survey Platform; Qualtrics, Provo, UT, USA), and both Spanish and English language versions were available. The survey was distributed to horticulture industry media outlets and trade journals (i.e., Hortidaily, CEAsight) and greenhouse growers. It was also distributed to greenhouse, nursery, and controlled environment agriculture (CEA) associations (i.e., Fruit and Vegetable Growers of Canada, Association of Vertical Farming, Association of Specialty Cut Flower Growers). Survey responses were collected from Aug 2023 to Mar 2024. Using the questionnaire, we asked questions regarding participants' awareness of the application of PAW to young plant production, their

willingness to learn (WTL) about and willingness to try (WTT) PAW, and their farm operation characteristics, including farm area, growing environment, crop type, production methods, using seed or seedling, how often they encounter low germination rate, whether they experienced poor young plant growth or difficult crops, their pre-planting seed treatments, and treatments to improve seedling growth. The full survey is available in the Supplementary Materials (Supplemental File 1). This study focused on how participants' WTL and WTT vary with their awareness of the function and farm operation characteristics of PAW. A total of 82 participants completed the full survey.

In our econometric analyses, the dependent variables (the indicators of WTL and WTT) were defined as dummy variables (1, if a participant is willing to learn about/try PAW; 0, if not); therefore, we used Probit models for our analysis. To show how Probit models work, we used the case in which WTL was the dependent variable as an example.

In the Probit model, Eqs. [1] and [2] defined the probability that a participant is willing to learn about PAW and the probability that the participant is unwilling to learn about it.

$$\begin{aligned} Pr(WTL_i = 1 | \text{Independent Variables}_i) &= \Phi(\beta' \text{Independent Variables}_i) \quad [1] \\ Pr(WTL_i = 0 | \text{Independent Variables}_i) &= 1 - \Phi(\beta' \text{Independent Variables}_i) \quad [2] \end{aligned}$$

In Eqs. [1] and [2],  $\Phi(\cdot)$  is the cumulative distribution function for standard normal distribution and  $WTL_i$  is the dependent variable (an indicator of whether participant  $i$  is willing to learn about PAW; 1, if participant  $i$  is willing to learn about PAW; 0, otherwise).  $\text{Independent Variables}_i$  represents the vector of size  $n$  of all independent variables.

With Eqs. [1] and [2], the log-likelihood function of the Probit model can be written as Eq. [3]:

$$\begin{aligned} \log L(\beta) &= \sum_{i=1}^n \{ WTL_i * \log \Phi(\beta' \text{Independent Variables}_i) \\ &\quad + (1 - WTL_i) * \log [1 - \Phi(\beta' \text{Independent Variables}_i)] \} \end{aligned}$$

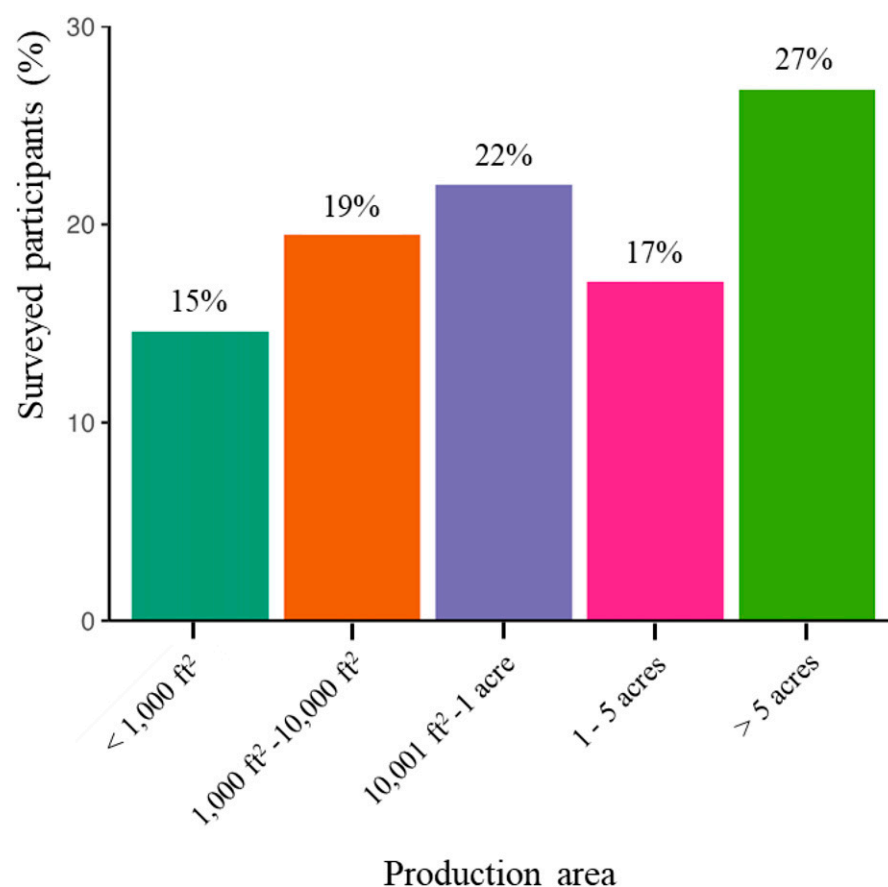


Fig. 2. Production area and type of operation (conventional, organic, or both) in surveyed participants' greenhouse and nursery operations (N = 82).

$$+(1 - WTL_i) * \log [1 - \Phi(\beta' \text{Independent Variables}_i)] \quad [3]$$

Using the maximum likelihood estimation, we can obtain the estimates satisfying the following:

$$\hat{\beta} = \text{argmax}\{\log L(\beta)\} \quad [4]$$

When the dependent variable is the indicator WTT, the method is the same.

We ran two sets of Probit estimations. In each set, there are two regressions with the dependent variables WTL and WTT, respectively. The difference between the two sets is the vector of independent variables. In the first set, this vector includes the production area, four indicators of growing environments (whether the participant uses greenhouse, high tunnel, outdoor container nursery, and indoor vertical farm as the growing environment), seven indicators of crop types (whether the participant plants berries, herbs, floriculture/ornamental crops, vegetables for production, vegetables for transplants, young plants, and other plants), two indicators of production methods (whether the participant uses conventional and organic production methods), an indicator of using seeds (whether the participant uses seeds), an indicator of using seedlings (whether the participant uses seedling), and an indicator of whether the participant was aware of the function of PAW. The second set of regressions tries to provide insights into how other factors impact WTT/WTL. Therefore, in addition to the independent variables in the first set, we added more variables to the vector: the frequency that the participant experienced lower germination than the labeled germination rate on seed packages, the frequency that the participant conducted preplanting seed treatments, the frequency that the participants encountered inconsistent/poor seedling growth, the frequency that the participant used treatments to improve seedling growth, and the interactions of preplanting seed treatment frequency and crop types.

## Results and discussion

The summary statistics and detailed definitions of the dependent and independent variables are shown in Table 1. Approximately 78% of respondents showed interest in learning about PAW,

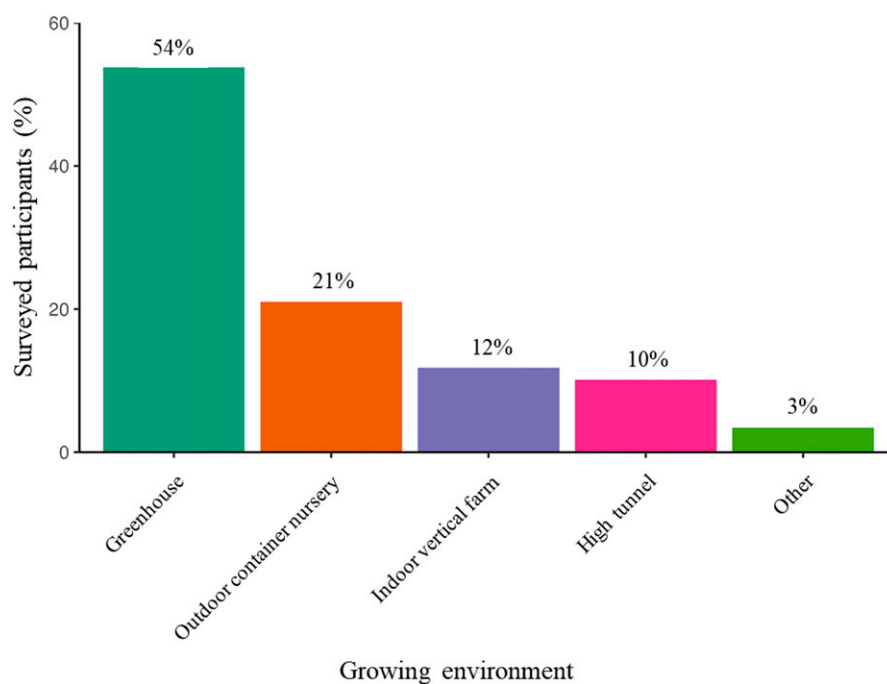


Fig. 3. Growing environments reported in surveyed participants' greenhouse and nursery operations (N = 82).

and 55% were willing to try PAW. The average area of greenhouse or nursery production was approximately 2.68 acres, with the largest number of respondents (27%) having greater than 5 acres of production area, but with a fairly wide distribution in size of operation (Fig. 2). In terms of growing environments, 54% used greenhouses, 10% used high tunnels, 21%

had outdoor container nurseries, and 12% had indoor vertical farms (Fig. 3). For crop types, the largest number of respondents grew floriculture ornamental plants (29%), 15% grew young plants, 16% grew vegetables for transplants, 12% grew herbs, and 5% grew berries (Fig. 4). For production methods, 60% used only conventional production methods, 17% used only organic

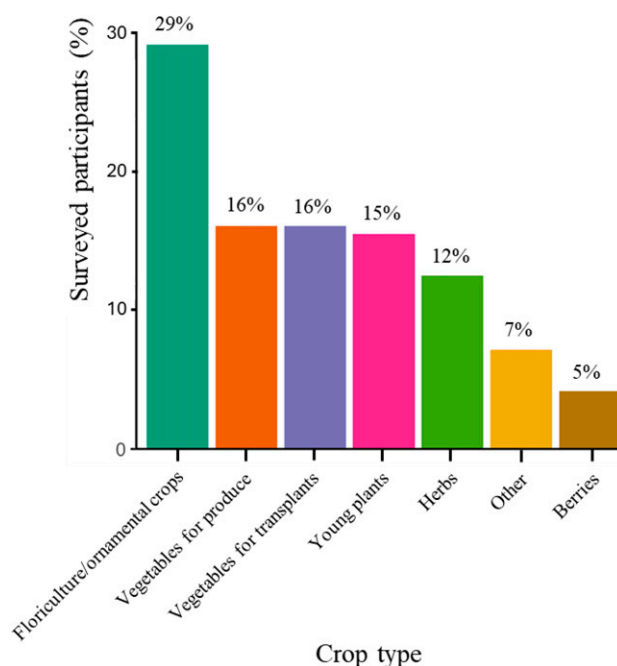


Fig. 4. Crop types in surveyed participants' greenhouse and nursery operations (N = 82).

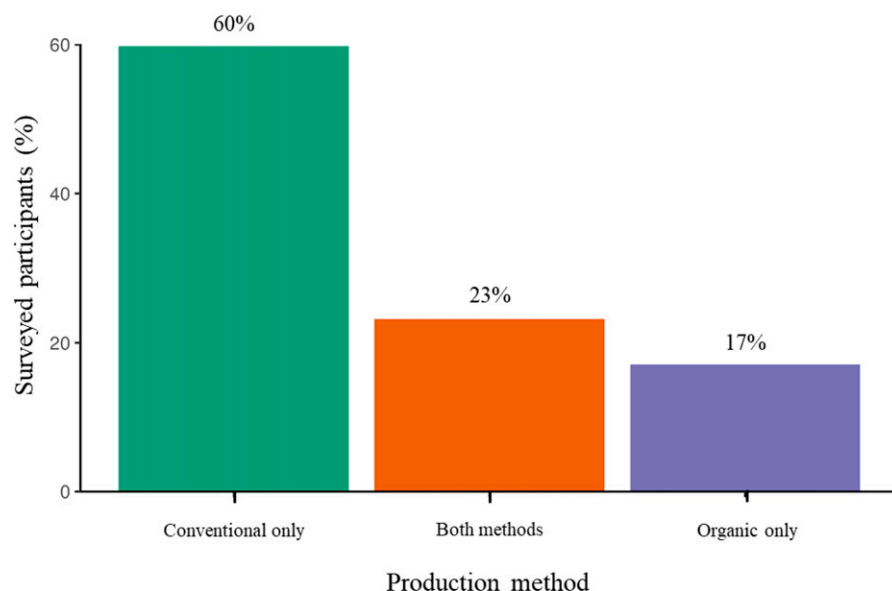


reported crops with seedling growth issues included begonia, vinca, herbs, peppers, lettuce, and perennials, among a great diversity of crops with issues (Supplemental File 2; Supplemental Table 2). The mean frequency rating for participants using treatments to improve seedling growth was 2.4 (Table 1).

Table 2 shows the results of the first set of regressions. Column (1) in Table 2 shows how participants' WTL varied with their farm operation characteristics and their awareness of the application of PAW for seedling performance. The coefficients of the production area, greenhouse indicator, herbs indicator, and seed using indicator were significantly positive, indicating that participants who had larger production area, used greenhouse in farm operation, planted herbs, or used seeds in production were more willing to learn about PAW. Column (2) in Table 2 presents the results regarding WTT. Similar to the results for WTL, the significantly positive coefficient of herbs indicator implied that participants who planted herbs were more willing to participate in trials with PAW. Participants who used outdoor container nurseries for farm operation were less likely to try PAW, while participants who used indoor vertical farms were more willing to try PAW.

Table 3 lists the results of the second set of regressions, which included additional and interactive factors affecting WTL and WTT. A comparison of the corresponding results of Tables 2 and 3 indicated that, after adding more variables into the models, most of the findings in the first regression set remained valid. The interaction between preplanting seed treatment frequency and crop type allowed us to understand how participants' seed treatment practices across different crops influence their WTL and WTT.

In the second set of regressions, the coefficient of using seeds was significantly negative for both regressions (Table 3), which was opposite to what we observed in the first set of WTL regression (Table 2). However, such differences can be attributed to the interaction of preplanting seed treatment and crop types revealing how existing seed treatments on specific crops impact a farmer's WTL or WTT PAW. For example, a farmer who sows seed that is by and large easy to germinate may have

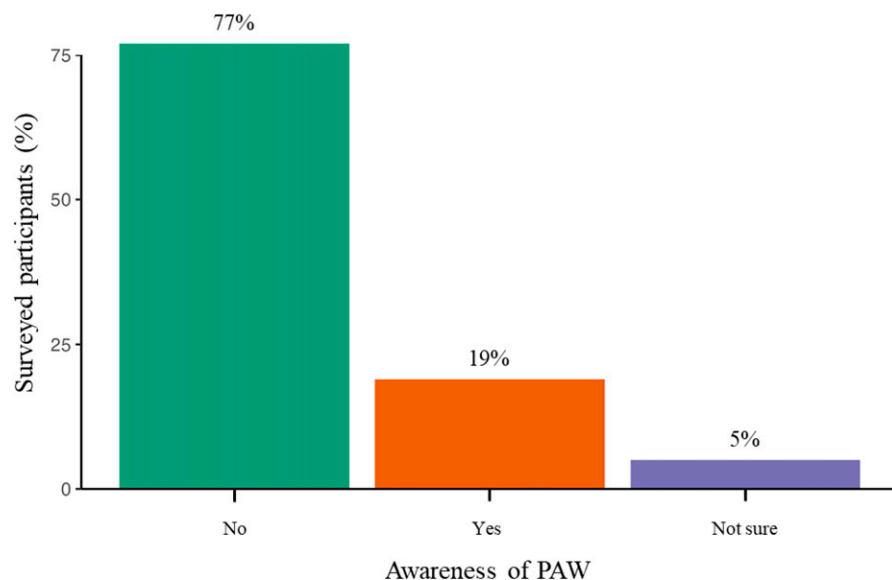


**Fig. 5. Production method reported in surveyed participants' greenhouse and nursery operations production methods (N = 82).**

production methods, and 23% used both organic and conventional (Fig. 5). Approximately 82% of participants used seeds and 73% used seedlings (data not shown). Only 19% of participants were aware of the function of PAW (Fig. 6).

For the experience of low germination rates for seeds (1 = never, 2 = sometimes, 3 = approximately half of the time, 4 = most of the time, and 5 = always), the average rating was 2.3, indicating that participants sometimes experienced lower germination rates than that labeled on seed packages (Table 1). Participants were

asked to write in crops that had the most frequent germination issues. Commonly reported crops with germination issues included perennials, tomatoes, lettuce, begonia, and peppers, along with a large diversity of crops (Supplemental File 2; Supplemental Table 1). In terms of preplanting seed treatment frequencies, the mean rating was 1.8 (1.8 was close to rating 2, which means "sometimes" based on the definition of the ratings). The mean rating for poor seedling growth was 2.2, indicating that participants sometimes but did not always experience poor seedling growth. Commonly



**Fig. 6. Awareness of plasma-activated water in agricultural applications by surveyed participants (N = 82).**

**Table 2. Factors impacting participants' willingness to learn (WTL) and willingness to try (WTT) plasma-activated water (PAW) based on the survey data of 82 US growers.**

| Variables                       | (1)<br>WTL about<br>PAW | (2)<br>WTT PAW<br>in trials |
|---------------------------------|-------------------------|-----------------------------|
| Area                            | 0.207**<br>(0.098)      | 0.0587<br>(0.064)           |
| Greenhouse                      | 1.362**<br>(0.616)      | 1.073<br>(0.679)            |
| High tunnel                     | 0.289<br>(0.642)        | 0.620<br>(0.552)            |
| Outdoor container nursery       | -0.358<br>(0.549)       | -0.935*<br>(0.491)          |
| Indoor vertical farm            | 1.173<br>(0.922)        | 1.456**<br>(0.729)          |
| Berries                         | -1.391<br>(0.941)       | -0.004<br>(0.746)           |
| Herbs                           | 1.237*<br>(0.709)       | 0.851*<br>(0.467)           |
| Floriculture/ornamental crops   | 0.139<br>(0.500)        | 0.184<br>(0.461)            |
| Vegetables for production       | -0.338<br>(0.595)       | -0.235<br>(0.440)           |
| Vegetables for transplants      | -0.609<br>(0.563)       | -0.692<br>(0.442)           |
| Young plants                    | -0.118<br>(0.536)       | -0.024<br>(0.427)           |
| Other plants                    | -0.012<br>(0.587)       | -0.053<br>(0.574)           |
| Conventional production methods | 0.046<br>(0.708)        | 0.577<br>(0.628)            |
| Organic production methods      | 0.632<br>(0.532)        | 0.510<br>(0.420)            |
| Using seed                      | 1.006*<br>(0.574)       | 0.448<br>(0.688)            |
| Using seedling                  | 0.230<br>(0.566)        | 0.385<br>(0.494)            |
| Aware of the function of PAW    | 0.432<br>(0.605)        | 0.307<br>(0.433)            |
| Constant                        | -1.904<br>(1.166)       | -2.429*<br>(1.333)          |
| Observations                    | 82                      | 73                          |

Standard errors in parentheses. \*\*\* $P < 0.01$ , \*\* $P < 0.05$ , \* $P < 0.1$ .

A significant positive coefficient indicates an increase in the dependent variable increasing the probability or likelihood of WTL or WTT.

A significant negative coefficient indicates an increase in the dependent variable decreasing the probability or likelihood of WTL or WTT.

less incentive to search for technologies to increase germination parameters. For participants who used seeds to plant berries, floriculture/ornamental crops, vegetables for production, young plants, or other plants, the higher preplanting seed treatment frequency was correlated with a higher WTL, suggesting economies of scale would justify the investment even if the benefit was relatively minor. In the first set of WTL regressions, such positive correlations were partially absorbed by the positive

coefficient of the “using seed” indicator. Apart from the WTL regression, after adding the interactions, most of the main effects of crop type indicators (such as berries, floriculture/ornamental crops, vegetables for production, young plants, or other plants) became significantly negative. This implied that when a participant did not use seeds in production, planting these crops correlated with lower WTL PAW. After all, it is only fitting that farmers will dedicate the time to understand and subsequently adopt a

new technology if they first see the potential of a perceived benefit in their operation.

Compared with the first set of regression (Table 2), more coefficients had similar significance values and trends (positive or negative) for both regressions in the second set, as seen for indicators greenhouse, outdoor container nursery, indoor vertical farm, and using seeds (Table 3), indicating that the correlation between WTL and farm operation characteristics and the correlation between WTT and farm operation characteristics may follow similar patterns, which was revealed by adding the interaction terms. Participants who experienced lower germination rates were more eager to use new technologies such as PAW to enhance seed germination (Table 3), which was consistent with previous studies that showed that growers adopt new cultivars or technologies to gain better germination rates, higher yields, and stronger resilience to growing environments (Mihretie et al. 2022; Toulabi et al. 2022).

We found that farmers with larger production areas were more willing to learn about PAW. This implied that larger farms are favorably disposed to allocate time to review the potential benefits of PAW. Individual reasons were inherent to each operation; however, historical data indicated that larger farms are more inclined to adopt new technologies and expend more resources deriving agricultural knowledge (Hu et al. 2022). They may have a greater interest in exploring new technologies and innovations that could enhance their agricultural practices, potentially leading to increased productivity and efficiency. Large farms tend to have more resources to invest in and experiment with new technologies such as PAW, limiting the overall risk. Farmers assume operational risk in decision-making and, therefore, will be averse to adopting novel technologies without first understanding them thoroughly (Lin 1991). This often includes a process of on-farm small-plot experimentation. Small-scale farms lack the extra land required for adequate experimentation (Uaiene et al. 2011) and opt for more traditional proven technologies that will, at minimum, maintain their profit margins (Hu et al. 2022).

**Table 3. Participants' willingness to learn (WTL) and willingness to try (WTT) plasma-activated water (PAW): Roles of preplanting seed treatments and crop types. The analysis is based on the survey data of 82 US growers.**

| Variables                                                           | (1)<br>WTL about<br>PAW | (2)<br>WTT PAW<br>in trials |
|---------------------------------------------------------------------|-------------------------|-----------------------------|
| Area                                                                | 0.772***<br>(0.292)     | 0.135<br>(0.083)            |
| Greenhouse                                                          | 3.007**<br>(1.349)      | 1.924**<br>(0.891)          |
| High tunnel                                                         | 0.815<br>(1.209)        | 1.143*<br>(0.688)           |
| Outdoor container nursery                                           | -3.394*<br>(1.893)      | -1.916***<br>(0.646)        |
| Indoor vertical farm                                                | 3.246*<br>(1.673)       | 1.947**<br>(0.816)          |
| Berries                                                             | -14.070*<br>(8.165)     | 2.574<br>(3.112)            |
| Herbs                                                               | 13.350*<br>(7.032)      | 2.876**<br>(1.435)          |
| Floriculture/ornamental crops                                       | -8.674**<br>(3.507)     | 1.062<br>(1.183)            |
| Vegetables for production                                           | -10.500**<br>(4.506)    | -0.410<br>(1.116)           |
| Vegetables for transplants                                          | 0.722<br>(3.654)        | -3.593**<br>(1.617)         |
| Young plants                                                        | -6.111**<br>(2.878)     | 0.986<br>(1.115)            |
| Other plants                                                        | -4.464**<br>(1.906)     | 1.743<br>(1.535)            |
| Conventional production methods                                     | -3.297<br>(2.131)       | 0.091<br>(0.749)            |
| Organic production methods                                          | -0.034<br>(1.102)       | -0.062<br>(0.544)           |
| Using seed                                                          | -5.770*<br>(3.256)      | -2.473*<br>(1.357)          |
| Using seedling                                                      | -2.521<br>(3.606)       | -0.415<br>(1.122)           |
| Aware the function of PAW                                           | -1.472<br>(1.820)       | -0.334<br>(0.544)           |
| Lower germination frequency                                         | 1.713<br>(1.171)        | 1.096**<br>(0.445)          |
| Preplanting seed treatments                                         | -5.583**<br>(2.385)     | 0.503<br>(0.747)            |
| Poor seedling growth                                                | -0.370<br>(1.401)       | 0.250<br>(0.392)            |
| Treatments to improve seedling growth                               | 0.629<br>(0.770)        | -0.096<br>(0.209)           |
| (Preplanting seed treatments) * Berries                             | 7.617*<br>(4.144)       | -0.876<br>(1.493)           |
| (Preplanting seed treatments) * Herbs                               | -9.389**<br>(4.337)     | -1.288<br>(0.851)           |
| (Preplanting seed treatments) * (Floriculture/<br>ornamental crops) | 7.389***<br>(2.763)     | -0.080<br>(0.629)           |
| (Preplanting seed treatments) * (Vegetables for<br>production)      | 7.971**<br>(3.424)      | 0.475<br>(0.742)            |
| (Preplanting seed treatments) * (Vegetables for<br>transplants)     | 0.614                   | 1.577*                      |

(Continued on next page)

Our results showed that farmers who use greenhouses or indoor vertical farms have greater interest in PAW. These farms typically place greater emphasis on the importance of environmental factors, such as water quality and disease management, because of the controlled nature of their operations. Furthermore, PAW has potential benefits for plant health and disease control; therefore, it aligns well with their existing priorities and practices. Additionally, running greenhouses or indoor vertical farms often requires significant investments in infrastructure, technology, and resources. Farmers with greenhouse or indoor vertical farm operations may have greater financial capacity to explore and adopt new technologies like PAW compared with those with smaller-scale or more traditional farming practices. On the contrary, farmers with outdoor container nurseries are less willing to learn or try PAW. Outdoor container nurseries may present unique challenges or constraints that limit the feasibility or effectiveness of integrating PAW into existing operations. Farmers in this sector may face practical barriers, such as limited access to water sources, infrastructure constraints, or labor-intensive production methods, which could lower their willingness to experiment with PAW. In a meta-analysis of factors that influence farmer WTP for agricultural innovations, cost was among the greatest factors limiting adoption, while adoption was increasingly favored as crop benefits increased and innovation improved environmental outcomes (Olum et al. 2020).

Another finding was that farmers who grew herbs showed great interest in PAW, but those who already used preplanting seed treatments more frequently on herbs were less interested in learning about PAW. It can be assumed that those who already use other preplanting seed treatments may be exhibiting conservativeness in altering a practice that is already paying dividends. However, farmers often use herbs to diversify their crop production (Davis 2012). Farmers who incorporate herbs into their operations may be more open to experimenting with new practices and technologies such as PAW. Herbs are often grown for their medicinal, culinary, or aromatic properties, and farmers who cultivate herbs may be more aware of the importance of natural solutions for crop management. They might have

Table 3. (Continued)

| Variables                                      | (1)<br>WTL about<br>PAW        | (2)<br>WTT PAW<br>in trials   |
|------------------------------------------------|--------------------------------|-------------------------------|
| (Preplanting seed treatments) * (Young plants) | (2.309)<br>3.872**<br>(1.953)  | (0.940)<br>-0.582<br>(0.629)  |
| (Preplanting seed treatments) * (Other plants) | 5.880***<br>(2.232)            | -0.635<br>(0.732)             |
| Constant                                       | 10.910**<br>(5.339)<br>(1.953) | -3.081*<br>(1.856)<br>(0.629) |
| Observations                                   | 82                             | 73                            |

Standard errors in parentheses. \*\*\*  $P < 0.01$ , \*\*  $P < 0.05$ , \*  $P < 0.1$ . We have tried to include the interactions between the variable “treatment to improve seedling growth” with crop types, but the models did not converge.

A significant positive coefficient indicates an increase in the dependent variable increasing the probability or likelihood of WTL or WTT. A significant negative coefficient indicates an increase in the dependent variable decreasing the probability or likelihood of WTL or WTT.

specific requirements for seed treatment methods based on the characteristics of the herbs or their farming practices, and PAW can potentially fulfill these requirements.

Our results provide several potential insights about farmers’ attitudes toward PAW from those who use seeds in their operations. These farmers may set high priorities for practices that optimize seed germination. Their WTL about PAW suggests a recognition of the potential benefits this technology could offer for enhancing seed germination, especially for those farmers who have more frequently used preplanting seed treatments for crops such as berries, floriculture/ornamental crops, vegetables for production, young plants, and other plants. They might see PAW as a promising tool for enhancing seed germination rates, promoting uniform emergence, and improving early plant growth, ultimately increasing crop yields and productivity. In contrast, farmers who rely on seedlings may purchase young plants from other specialty producers or already have established practices and systems in place for their crop production. These practices may include specific methods for seedling care, transplanting, and crop management, but not seed germination. As a result, they are less inclined to explore new technologies like PAW, especially if they perceive them as incompatible with their existing practices. Previous literature has shown that compatibility significantly impacts growers’ adoption of new technologies and is the strongest predictor of the likelihood of adoption (Kalauni et al. 2024).

## Implications and conclusions

In agriculture, PAW is a promising innovative technology that offers potential benefits for plant health, disease control, and crop productivity. However, the successful adoption of PAW depends on farmers’ WTL and WTT. We conducted a survey to assess farmers’ receptiveness to PAW. Our results provide important implications for marketers, researchers, and policymakers to tailor marketing, outreach, and educational programs to address specific concerns and barriers to adoption.

The findings regarding farmers’ interests in PAW have significant implications for both marketers and policymakers in the agricultural sector. First, target marketing efforts toward farmers with greenhouse or indoor vertical farm operations might be effective because these farmers show a greater interest in learning and trying new technologies such as PAW. Marketing campaigns can highlight the potential benefits of PAW for plant health and disease control and emphasize its alignment with existing practices in greenhouse and indoor protection.

Conversely, farmers in the outdoor container nursery sector exhibit lower WTL or WTT PAW, indicative of a need for tailored research and marketing strategies that address the challenges and constraints faced by this group. Moreover, promoting the adoption of PAW among outdoor container nursery farmers may involve providing targeted training programs, technical assistance, and financial assistance, including incentives

or subsidies to overcome practical farm operational or financial barriers.

Furthermore, the findings related to herb farmers underscore the importance of understanding herb farmers’ specific preferences and requirements when introducing new technologies such as PAW. Marketing efforts should emphasize the potential benefits of PAW tailored to herbs. Policymakers may also explore opportunities to support research and development initiatives focused on how PAW applications can help herb production and enhance this technology’s relevance to herbs.

Finally, marketing efforts aimed at promoting PAW adoption should emphasize its potential benefits for enhancing seed germination rates, promoting uniform emergence, and improving early plant growth, which can resonate with farmers who intend to improve seed germination rates, especially those growing berries, floriculture/ornamental crops, vegetables for production, and young plants. Marketing campaigns can use case studies or testimonials from farmers who have successfully used PAW to improve seed germination outcomes and provide real-world examples to showcase its effectiveness.

Overall, the insights of this study highlight the importance of targeted marketing strategies and policy interventions to facilitate the adoption of PAW among different sectors of the agricultural industry.

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