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Impact of pulsed electric field treatment on barley germination for malting

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ABSTRACT

The malting process takes one week to steep, germinate, and kiln barley to make malt. Making quality malt is critically important to achieve the desired attributes of the finished beer, and the process is time-intensive and costly. Malt quality is assessed by indicators including β-glucan quantity, α-amylase activity, Free Amino Nitrogen (FAN) content, and overall extract concentration in the finished malt. Here, we report Pulsed Electric Field (PEF) treatment of barley to accelerate malt production. A small-scale trial of 250 g to 1.00 kg barley, was evaluated for germination at two PEF treatment conditions, generically referred to as "low" and "high", that resulted in increased barley rootlet length during germination of 1.3 mm longer than was observed for the control. Large-scale trials of 1.00 kg–3.00 kg barley, resulted in an increase in germination rate and a decrease of β-glucan concentration in the PEF treated barley. Micromalted barley using PEF parameters of 1.0 kV/cm and 15.0 kJ/kg displayed a reduction in β-glucan concentration by 38%, and increase in malt extract by 1.5%, FAN by 6.2%, and α-amylase by 8.4%, supporting the hypothesis that PEF treated barley generates more and better malt, leading to greater efficiency in the beer making process.

1. Introduction

Idaho is the top producer of barley in the United States, accounting for roughly 33 g/100 g of domestic production, with 80 g/100 g of the annual crop being converted into malt (U.S. Department, 2023). In addition to barley, Idaho also generates more malt than any other state, but ranks 39th in beer production, producing only 38,483 barrels of beer annually (U.S., 2023). From an economic perspective, revenue increases with processing, which is to say that malt generates higher profit margins than barley, but beer is even better than malt. Thus, to improve the economic resilience for barley processors, any efficiency improvements in malt production is highly desirable.

To produce malt, barley must be steeped, germinated, and kilned. Raw barley that has been cleaned and dried is steeped in a 21 °C water bath for 28–30 h until the moisture content reaches between 42 and 46 g/100 g (Guido & Moreira, 2013; Brookes, Lovett, & MacWilliam, 1976). The water content is critical for the seed to achieve optimal oxygenation for germination. Hormone secretion of gibberellic acid within the barley initiates germination, which leads to the activation of myriad enzymes, including α-amylase and β-amylase (Gómez-Cadenas, Zentella, Walker-Simmons, & Tuan-Hua David Ho, 2001). The amylase enzymes catalyze the degradation of the starchy endosperm into useable sugars for the growing embryo (Fox, 2018). As the malting process progresses, the barley seed is germinated for a prescribed amount of time, depending on the particular malt variety (Fox, 2009). A study by Bettenhausen et al. looked at six different varieties of barley, and their effect on finished beer flavor. Metabolomic profiling concluded that each variety of barley imparts different flavors into the final beer, with the Full Pint variety being associated with a fruity flavor and the Honeycomb variety associated with a cereal flavor (Bettenhausen et al., 2018). As germination progresses, a coleoptile and radicle emerge from the barley seed. The coleoptile gradually turns into the first leaf and the radicle transforms into the primary root (Ha, 2023). It is critically important for the barley to maintain a moisture content of 44–46 g/100 g initially achieved in the steeping step. This optimal moisture level is retained in the barley using temperature and humidity controlled

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environmental conditions throughout germination. Proper moisture content during germination allows for production of essential enzymes, which break down starch into fermentable sugars, including glucose and fructose, that are used by yeast in the mashing step to generate adenosine triphosphate (ATP) (Hough, Briggs, & Stevens, 1971). β-Glucan is a polysaccharide that makes-up the cell walls of the endosperm and is broken down into glucose during germination. Low β-glucan levels indicate that adequate enzymatic breakdown of the endosperm has occurred, allowing the soluble material to be separated from insoluble (Dalgliesh, 1979). The soluble material will undergo further enzymatic break-down into simple sugars that will be utilized in the mash.

After the barley has germinated for 68–72 h, the growth process is halted by kilning, a two-step drying method (Schuster, 1962). The malt is first dried at temperatures between 59°C and 67 °C to reduce the water content of the seed from 42 to 46 g/100 g down to 5 g/100 g. The kiln temperature is then slowly increased up to 79 °C to achieve a final barley moisture content of 4 g/100 g, which contributes to the desired flavor and color profiles for the mash and final product (Kalb, Seewald, Hofmann, & Granvogl, 2022). The amount of time that grain is malted impacts the starch to enzyme ratio, and each step of the process has to be optimally timed to achieve the highest quality malt. If the barley is allowed to steep too long, the result is earlier germination with complete enzymatic breakdown of the starchy endosperm and its contents, and low protein levels (Bamforth, 1985). In the fermentation step, nitrogen is needed for yeast survival and proliferation (Buiatti, 2009). During germination, storage proteins are broken-down into individual amino acids; these amino acids along with other nitrogen containing compounds like ammonia, constitute the Free Amino Nitrogen (FAN) (Hill & Stewart, 2019).

Pulse Electric Field (PEF) can be used to electro-stimulate, reversibly electroporate, or irreversibly electroporate cells. The review by Javanov and Volkov details how electric currents have been used to induce plant movement and stimulate plant growth (Jovanov & Volkov, 2012). Electroporation is dependent on reaching the transmembrane potential to create and maintain pores in the cell membrane, which allows for molecules to exit or enter the cell (Kandušer & Miklavčič, 2009). The use of PEF has been found to enhance the extraction of sugar from sugar beets and potatoes, inactivate microbial growth, as well as enhance juice extraction from oranges (Barba et al., 2015; Hill, Ostermeier, Töpfl, & Heinz, 2022; Buckow, Ng, & Toepfl, 2013). PEF has also been shown to increase the germination rate of wheat seed by 10%, as well as increase resistance to cold and salt stress (Akdemir Evrendilek et al., 2021). A PEF treatment of 5 kV/cm before sowing, was shown to increase carotenoid content of red clover sprouts (Gałązka-Czarnecka, Korzeniewska, Czarnecki, Kiełbasa, & Dróżdż, 2020). Red clover sprouts are eaten by many people for their health benefits, which come from carotenoids like zeaxanthin and β-carotene. A study by Zhang et al. was the first to demonstrate increased α-amylase activity when PEF treatment was applied to barley that had been steeped for 28 h (Zhang et al., 2019). Their work showed that PEF increased gene expression of Amy6-4, the gene responsible for synthesizing α-amylase. The increased α-amylase activity accelerated germination time for the barley as more digestible sugars were made available. Another study by Statsyuk et al. showed that low-frequency PEF treatment increased the percent germination rate and average coleoptile length of corn seeds when compared to the untreated control (Statsyuk, Vorobyev, & Smetanina, 2021). The study concluded that PEF treatment of corn accelerated germination by 27.6%, and resulted in a 21.2% increase in coleoptile length when compared to the control. A third study by Dymek et al. showed that PEF treatment of barley after steeping for 24 h led to decreases in root growth and α-amylase levels, but did not affect barley metabolic activity (Dymek et al., 2012). Lastly, Moon and Chung reported a germination rate increase of 1.1–2.8% for tomato seeds with an applied electrical current when compared to no electrical current. The authors concluded that using electric field ranges of between 4 and 12 kV/cm, and magnetic field strengths between 3 and 100 G, for short periods of time (30–45 s) increased the percent germination of the tomato seeds by 1.1–2.8% (Moon & Chung, 2000). The aim of the current study is to evaluate PEF treatment conditions for optimal reduction in barley germination time during the malting process.

2. Materials and methods

2.1. Malting materials

2.1.1. Barley

The raw Voyager variety barley from the 2022 harvest was used for all experiments, and the barley was donated by Anheuser-Busch (Idaho Falls, ID).

2.1.2. PEF system

PEF treatment of raw barley was performed prior to steeping, using the Elea PEF-Pilot Dual system in either an 800 mL or 9.6 L treatment cell, at the desired field strength and specific energy. Field strength has been described as the potential energy, and is the voltage applied over a certain distance (McDonald, Lloyd, Vitale, Petersson, & Innings, 2000). Specific energy equates to kinetic energy, and is the amount of energy required to move a unit of mass (Chou, Chua, Ho, & Ooi, 2004). PEF machine settings were kept consistent throughout the study with electrode distances of 8 cm for the 800 mL treatment cell and 24 cm for the 9.6 L treatment cell. A pulse width of 6 μs was retained throughout the study and was selected because it is the medium setting for the Elea PEF-Pilot Dual, where the system performs optimally. PEF treatment consisted of adjusting machine voltage to meet the desired field strength levels of 0.5, 1.0, and 3.0 kV/cm, with the total machine voltage set to 24 kV, at a frequency of 20 Hz. The barley was PEF treated at the assigned specific energy levels of 0.5, 1.0, and 5.0 kJ/kg.

2.1.3. Steeping

The steeping protocol was consistent for all trials. Prior to PEF treatment, raw barley weights were measured with an OXO 2.3 kg food scale. After PEF treatment, each batch of barley was placed into a separate 18.9 L bucket, covered with tap water (21 °C), and aerated for 28 h using a Skywin Aquarium DC Air Pump (500 mL per min. cap.).

2.1.4. Germination materials

For the small-scale trials (250 g - 1.00 kg), steeped barley weights were taken on a Torbal AGZN200 top loading balance to the nearest 0.0001 g. Rectangular Pyrex® storage containers (1.5 L) were used as germination trays. A Benchmark Scientific MyTemp Mini Digital Incubator (model #H2200-HC) was used as a germination chamber. The temperature of the germination chamber was set to 21 °C, and the humidity was retained at or above 90% for the duration of germination. The humidity was kept constant by hand-stirring and wetting barley with a spray bottle, two times daily. Radicle emergence of barley seedlings was measured with a Fisher brand Traceable® digital caliper to the nearest 0.01 mm, using 10 seeds that were randomly selected, rootlet length measured, and then returned to bulk sample. The moisture content of barley after steeping, germination, and kilning were measured on an OHAUS MB120 moisture analyzer using a standard drying program at a temperature of 105 °C, switch-off criterion of A60 (1 mg per 60 s) and a display mode of g/100 g MC.

For the large-scale trials (1.00 kg–3.00 kg), steeped barley weights were taken on an OXO 2.3 kg food scale to the nearest 0.01 g. Mid-grade polyethylene reversible tarps (12′ × 16′) were used for the duration of germination. A temperature-controlled storage room was used as a germination chamber, the tarps were placed on a cement floor, and the room was kept at 24 °C to maintain a germination temperature of 21 °C. Radicle emergence measurements and moisture content parameters for the large-scale trials were the same as the small-scale trials mentioned above.

2.1.5. Kilning materials

The kilning protocol for all small-scale and large-scale trials was the same, with the exception that the large-scale trials utilized two drying trays instead of one to accommodate the larger mass of green malt (3.00 kg). The germinated barley was dried using a Harvest Saver tray dryer (Model #R-5A), with each test case being placed on a separate tray. Kilning started at 59 °C with a fan speed of 4 (high) and ended at 79 °C with a fan speed of 2 (low), for a total drying time of 26 h. The kilned barley was de-rooted using a fine-mesh stainless steel strainer (S/S 18/8) and placed in individually marked storage bags for shipment.

2.2. Malting methods

2.2.1. PEF treatment methods

The PEF treatment methods were consistent throughout (small-scale and large-scale) testing, the raw barley was covered with tap water (21 °C, conductivity (σ) = 0.31 mS/cm), and allowed to soak for 2 min prior to PEF treatment. Small-scale PEF optimization consisted of three rounds, where the amount of barley was 250 g, 500 g, and 1.00 kg of steeped barley, respectively. The small-scale trials tested a wide range of PEF treatment settings intended to minimize energy usage to achieve maximal benefit to germination (Table 1).

From the 250 g testing, a medium and high PEF treatment was selected for scale-up to 1.00 kg. For the 1.00 kg scale-up PEF treatment conditions were either "low" or "high", where "low" PEF treatment consisted of voltage on the Elea PEF-Pilot Dual system set to a field strength and specific energy of 1.0 kV/cm and 14.0 kJ/kg, respectively. The "low" PEF treatment was applied to 1.00 kg of raw barley, placed into a 9.6 L PEF treatment cell, to which was added 1.5 L of tap water and allowed to soak. The "high" PEF treatment was conducted at a voltage on the Elea PEF-Pilot Dual system that was adjusted to a field strength and specific energy of 3.0 kV/cm and 20.0 kJ/kg, respectively. In the "high" treatment level experiments, 250 g of raw barley was placed into an 800 mL PEF treatment cell to which 400 mL of tap water was added and allowed to soak. Because of capacity restraints of the 800 mL treatment cell, the "high" treatment was broken into 250 g batches with a total of 1.00 kg of barley being treated. All test cases, the control, low PEF treatment, and high PEF treatment, were put in separate 18.9 L buckets and each bucket was filled with fresh tap water. An aquarium aerator was placed in each bucket and barley was allowed to steep for 28 h. The small-scale PEF test cases are summarized in (Table 2).

The large-scale results are summarized in (Table 3), with the "low" PEF treatment level experiments for 1.00 kg of raw barley that had been placed that into the 9.6 L PEF treatment cell, to which was added 1.5 L of water and allowed to soak. In the "high" treatment experiments, 375 g of raw barley was placed into the 800 mL PEF cell to which 400 mL of tap water was added and allowed to soak. All "low" and "high" field strength experimental conditions were repeated with a total of 3.00 kg of PEF treated barley for each test case. All test cases, the control, low PEF treatments, and high PEF treatments, were steeped in the same manner as test cases in the small-scale trials.

Table 1
Small-scale (250 g) PEF parameter settings for "low", "medium", and "high" test cases.

PEF Treatment Level	Sample	Field Strength (kV/cm)	Specific Energy (kJ/kg)
low	A	0.5	0.5
low	B	0.5	1.0
low	C	0.5	5.0
medium	D	1.0	1.0
medium	E	1.0	5.0
medium	F	1.0	10.0
medium	G	1.0	14.0
high	H	3.0	1.0
high	I	3.0	5.0
high	J	3.0	10.0
high	K	3.0	20.0
control	L	None	None

Table 2
Small-scale (1000 g) PEF parameter settings for "low" and "high" test cases.

Test Case	Field Strength (kV/cm)	Specific Energy (kJ/kg)
Control	None	None
Low	1.0	14.0
High	3.0	20.0

Table 3
Large-scale PEF parameter settings for "low" (A-D), control (E), and "high" (F-I) test cases.

PEF Treatment Level	Sample	Field Strength (kV/cm)	Specific Energy (kJ/kg)
low	A	1.0	5.0
low	B	1.0	10.0
low	C	1.0	15.0
low	D	1.0	20.0
control	E	None	None
high	F	3.0	5.0
high	G	3.0	10.0
high	H	3.0	15.0
high	I	3.0	20.0

2.2.2. Steeping index

The steeping index protocol for all small-scale and large-scale trials was consistent. During the steeping process the barley kernels were evaluated every 4 h and graded according to their degree of hydration or the amount of water that can enter the barley seed in a set amount of time, according to the Chapon test (Wainwright & Buckee, 1977). The Chapon test procedure is as follows: 50 seeds of each test case were taken from the 18.9 L bucket (starting with A and ending with I, one at-a-time) and boiled for 30 s in tap water. The barley kernels were then rinsed with cool tap water and cut in half lengthwise. For evaluation, one half of each barley kernel was assessed and assigned to 0–25 g/100 g, 25–50 g/100 g, 50–75 g/100 g or 75–100 g/100 g hydration. The number of kernels assigned to each hydration level were then combined and multiplied by a point value of 1–4. The hydration index for a particular test case at a particular time is the sum of all scores.

2.2.3. Germination methods

For the small-scale trials, the contents of each 18.9 L bucket were filtered through a strainer to collect the barley. The steeped barley was weighed and 1.00 kg was placed in each of the three labeled containers (6.5″ × 8.5" × 2.0″) for germination. During the 68-h. germination period, each test case was taken from the incubator and transferred into a larger container, sprayed with nanopure water, lightly hand-mixed, and again sprayed with nanopure water to ensure humidity levels were maintained. The turning of the barley was performed twice-a-day, with radical emergence being measured at the first turning. For each test case, 10 seeds were randomly selected and rootlet length was measured for each seed. After lengths had been recorded for a particular test case, all seeds were transferred back into the labeled container with the bulk sample and returned to the incubator at 21 °C. The labeled containers were rotated from top shelf to middle shelf, middle shelf to bottom shelf, and bottom shelf to top shelf to ensure that all test cases experienced the same incubator conditions.

For the large-scale trials, the contents of each 18.9 L bucket were filtered through a strainer to collect the barley. The steeped barley was weighed and 3.00 kg was placed on labeled section of tarp (A-I). During the germination period, each test case was lightly sprayed with

nanopure water, lightly hand-mixed, sprayed again with nanopure water and evenly spread-out on the labeled section of tarp. The turning of the barley was performed twice-a-day, with rootlet length being measured at first turning. For each test case, 10 seeds were randomly selected and rootlet length was measured for each seed, which were then returned to the bulk sample.

2.2.4. Kilning methods

After germination, each test case was weighed and spread-out on separate dehydrator trays and placed in the dehydrator, which had been pre-set to 59 °C, and the fan speed set on 4 (high). The kilning process using a commercial dehydrator was adapted to simulate industry kilning. The 26-h. drying process is outlined in (Table 4). After the final kilning step, each test case was removed from the dehydrator tray and weighed. The kilned barley was then de-rooted by hand using a Number 16 (8" diameter) medium-sized U.S. Standard Testing Sieve with a 0.0469" (1.18 mm) nominal sieve opening and a wire diameter of 0.63 mm. The de-rooted barley was weighed again and packaged for shipping.

2.2.5. Micromalting

Micromalting testing was done using a Newmalt Micromalter (Joe White Malting Systems, Adelaide, Australia). Grains were steeped at 15 °C, germinated at 18 °C, and kilned at 50–90 °C. The malting program used is detailed in (Table S1).

2.2.6. Malt analysis

Malt analysis testing for β-glucan, extract, Free Amino Nitrogen (FAN), and α-amylase was performed by Anheuser-Busch (Idaho Falls, ID). In short, β-glucan levels are measured by fluorescence spectroscopy, where the intensity of a fluorochrome is directly proportional to the amount of β-glucan present. Extract is the sum of all the carbohydrates, protein, and other soluble components in the finished malt and provides an indication of the malts overall fermentability and alcohol yielding potential (Wrigley, Batey, & Miskelly, 2017). To measure extract concentration, a mixture of ground malt and salt water is heated then filtered, the density of the filtered extract is then recorded (Pahl, Meyer, & Biurrun, 2016). FAN concentration is measured by reaction of primary amines with o-phthaldialdehyde (OPA), and the intensity of absorbance is measured at 340 nm with concentrations ranging from 145 to 188 mg/L according to the official Wort-12 ASBC method (ASBC Methodsof Analysis, 1975 method Wort-12). The concentration of α-amylase is measured spectrophotometrically at an absorbance of 660 nm, based on the rate of breakdown of a β-limit dextrin/malt solution (Cerkal et al., 2009).

3. Results

3.1. Soak-time testing

Soak-test trial results indicate that a 2 min soak-time, or a moisture content of 15 g/100 g, of raw barley in tap water prior to PEF treatment resulted in a 1.03 mm increase in rootlet length after 68 h of germination, when compared to the control, from 13.85 mm in the control barley to 14.88 mm in the PEF treated barley (Fig. S1).

Table 4
Kilning steps in malting process for commercial dehydrator.

Dry Step	Temperature (°C)	Fan Speed	Duration (H:MM)
1	59	4	5:00
2	63	4	4:10
3	66	4	5:00
4	67	4	5:00
5	72	4	2:20
6	74	4	0:20
7	76	3	1:25
8	76	2	0:15
9	79	2	2:10

3.2. Small-scale

Small-scale results confirmed that PEF treatment did not stunt, and may potentially stimulate barley germination, as demonstrated by the observation that PEF treated barley appeared to exhibit greater radical emergence as compared to the control (Fig. 1). Steeping index results for the small-scale trials showed that it took over 15 h for all test cases, (control, low, and high) to change in degree of hydration (Fig. S2). Small-scale results showed that field strengths of 1.0 kV/cm and 3.0 kV/cm led to elongated rootlet length as compared to the non-treatment control (Fig. 2). Small-scale results indicated that PEF treament increases rootlet length, leading to a scaled-up trial from 1.00 kg to 3.00 kg for the large-scale trials (Fig. 3).

3.3. Large-scale

PEF treatments consisted of testing two different field stengths at four specific energies. The two field strengths of 1.0 kV/cm and 3.0 kV/cm that were tested in the small-scale, were retained for testing, while specific energies were varied from 5.0 kJ/kg to 20.0 kJ/kg (Table 3). It was decided that in the large-scale, steeping index collection would start at 16, 20, 24, and 28 h. The steeping index results at 28 h indicate that all low (A, B, C and D) and 2 high (F and I) PEF treatments had lower Steep Index scores, or a higher degree of hydration than the control (E), with a PEF treatment of 1.0 kV/cm and 10.0 kJ/kg (B) having the highest degree of hydration (Fig. S3). Because PEF treatment conditions for trial B provided the most hydrated barley compared to control (E), a paired *t*-test was performed. No signifacant difference was found between the PEF treatment of 1.0 kV/cm & 10.0 kJ/kg and the control, with a p-value of 0.4110. Day 3 germination results showed that four PEF treatments: (B) 1.0 kV/cm and 10.0 kJ/kg, (C) 1.0 kV/cm and 15.0 kJ/kg, (D) 1.0 kV/cm and 20.0 kJ/kg, and (F) 3.0 kV/cm and 5.0 kJ/kg all had longer rootlet development than the control (Fig. S4). Spectrophotometric results of four PEF treatments: (B) 1.0 kV/cm and 10.0 kJ/kg, (C) 1.0 kV/cm and 15.0 kJ/kg, (D) 1.0 kV/cm and 20.0 kJ/kg, and (G) 3.0 kV/cm and 10.0 kJ/kg all had desired lower β-glucan levels than the control (Fig. S5). Moisture anlaysis of both "low" (A-D) and "high" (F-I) PEF treament levels are similar to the control (E) at all points in the malting process after steeping, germination, and kilning (Table S2), with consistent moisture content from steeping throughout germination.

A micromalting trial was performed to better replicate the industry malting process and confirm the large-scale results. The micromalter allowed for the whole malting process to be done in one vessel under

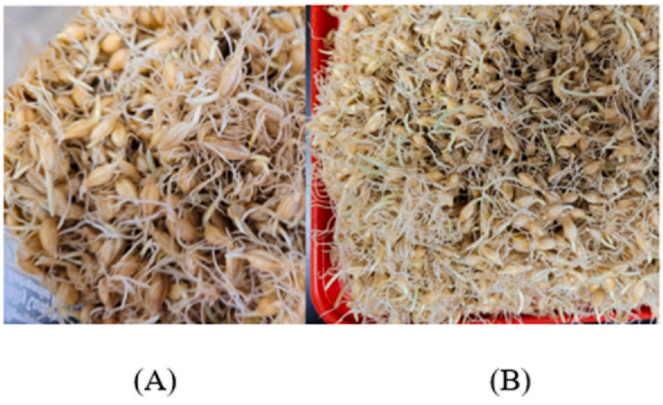

Fig. 1. Day 3 barley germination, where control (A), and PEF treatment at a field strength of 1.0 kV/cm and a specific energy 14.0 kJ/kg (B), both show robust radical emergence.

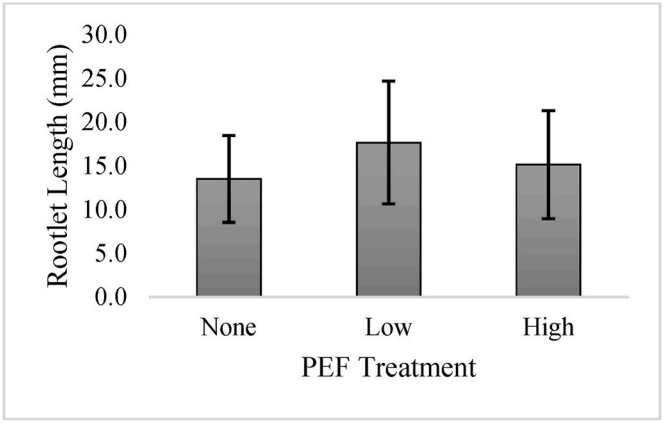

Fig. 2. Day 3 germination results for 1 kg sample size, where control is none, "low" is 1.0 kV/cm and 14.0 kJ/kg, and "high" is 3.0 kV/cm and 20.0 kJ/kg, n = 3.

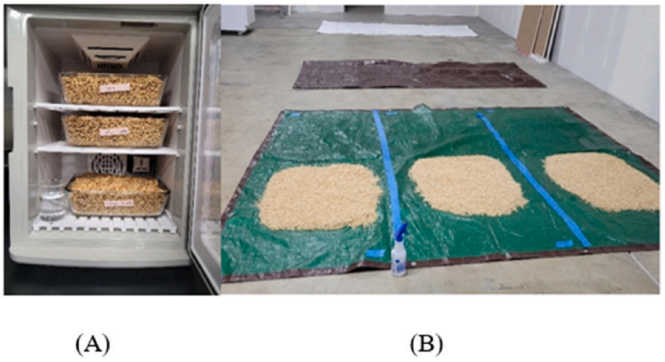

Fig. 3. Germination conditions for small-scale and large-scale, where 1 kg sample sizes (A) were scaled-up to 3 kg sample sizes (B).

strict time and temperature conditions. A control and three PEF treatments were tested in the micromalter: 1.0 kV/cm and 5.0 kJ/kg, 1.0 kV/cm and 15.0 kJ/kg, and 3.0 kV/cm and 15.0 kJ/kg. The micromalter results showed that both the 1.0 kV/cm and 15.0 kJ/kg and 3.0 kV/cm and 15.0 kJ/kg PEF treatments had a lower final concentration of β-glucan than the control, from 199 mg/L in the control malt to 123 mg/L and 152 mg/L in the PEF treated malts, respectively (Fig. 4). Unpaired t-tests were performed and a significant difference was found between the PEF treatment of 1.0 kV/cm and 15.0 kJ/kg and the control with a p-value of 0.0233 and the PEF treatment of 3.0 and 15.0 kJ/kg and the control with a p-value of 0.0281. The micromalter results also displayed that the 1.0 kV/cm and 15.0 kJ/kg PEF treatment had a higher extract concentration over the control, with an increase of 1.2 mg/L (1.5%), from 80.8 mg/L in the control malt to 82.0 mg/L in the PEF treated malt (Fig. 5). An unpaired *t*-test was performed and a significant difference, with a p-value of 0.0201, was determined between the PEF treatment of 1.0 kV/cm and 15.0 kJ/kg and the control. Both FAN levels and α-amylase activity increased for PEF treated malt compared to non-PEF control, with values ranging from 218.5 mg/L to 233.0 mg/L for FAN, and 73.0 mg/L to 79.7 mg/L for α-amylase. The results of micromalting trials are summarized in Table 5.

4. Discussion

The barley was subjected to a 2-min. soak in water prior to PEF treatment, and the result following PEF treatment was a 1.1% increase in rootlet length, over the non-PEF control. The aim of the small-scale experiments was to optimize PEF conditions, to achieve faster barley germination. The aim of the large-scale experiments was to refine PEF parameters, to achieve consistent or better germination rates than observed in the small-scale trials. The small-scale results indicated that a medium field strength and higher specific energy (1.0 kV/cm and 14.0 kJ/kg) provided the fastest rate of germination. In the large-scale trials, a more systematic approach was taken when it came to the specific energy parameter, varying specific energy in 5.0 kJ/kg increments from 5.0 kJ/kg to 20.0 kJ/kg. Steeping index results for both the small-scale and large-scale showed that the full 28 h of steeping was needed for all test cases to reach the 50–75 g/100 g hydration window, and that PEF treatment did not have a significant effect on the degree of hydration in the steeping process. Moisture analysis after steeping, germination, and kilning provided similar results with no significant differences between the PEF treatments and the control; the steeped barley moisture content ranged from 43.21 g/100 g to 46.04 g/100 g, germinated barley moisture ranged from 47.34 g/100 g to 49.51 g/100 g, and kilned barley moisture ranged from 3.04 g/100 g to 3.59 g/100 g. Steeping index and moisture content data indicate PEF treatment does not significantly impact the water content of the barley throughout the malt process.

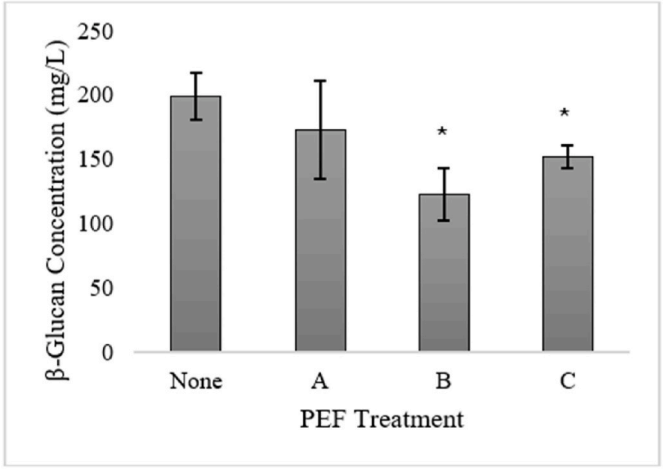

Fig. 4. β-Glucan concentration (mg/L) results for micro-malted barley, comparing a control to three different PEF treatment levels (1.0 kV/cm and 5.0 kJ/kg (A), 1.0 kV/cm and 15.0 kJ/kg (B), and 3.0 kV/cm and 15.0 kJ/kg (C)), n = 3, * indicate significant difference from control value.

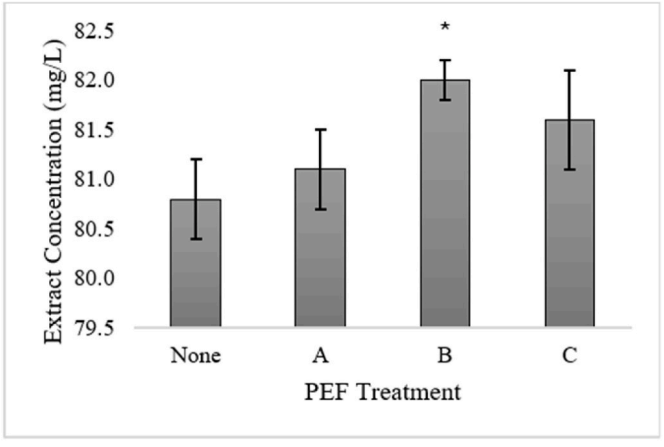

Fig. 5. Extract concentration (mg/L) results for micromalted barley, comparing a control to three different PEF treatment levels (1.0 kV/cm and 5.0 kJ/kg (A), 1.0 kV/cm and 15.0 kJ/kg (B), and 3.0 kV/cm and 15.0 kJ/kg (C)), n = 3, * indicate significant difference from control value.

Table 5
Micromalting results for β-glucan, extract, FAN, and α-amylase.

	PEF Treatment			
	None (mg/L)	A (mg/L)	B (mg/L)	C (mg/L)
β-Glucan	199.00 ± 18.38	173.00 ± 38.18	122.67 ± 20.03	152.33 ± 8.74
Extract	80.80 ± 0.42	81.10 ± 0.42	82.03 ± 0.21	81.60 ± 0.53
FAN	218.50 ± 2.12	138.00 ± 120.21	233.00 ± 6.08	242.00 ± 6.00
α-Amylase	73.00 ± 2.55	75.50 ± 0.28	79.93 ± 0.47	86.03 ± 2.87

5. Conclusion

PEF trials were conducted on 1.00 and 3.00 kg batch sizes of barley to identify optimal treatment parameters to accelerate the rate of germination during malting. The best PEF conditions to induce electrostimulation of barley increased the rate of germination by 2.9%, equating to root length elongation of 1.0 mm/h more than the control, when the temperature was kept at 21 °C and humidity maintained above 90%. PEF field strength of 1.0 kV/cm and a specific energy of either 14.0 kJ/kg (small-scale) or 15.0 kJ/kg (large-scale) provided superior overall growth rate compared to the non-PEF control, with rootlet length increasing by 1.0–1.1 mm/h. Analysis of the micromalted barley produced using PEF parameters of 1.0 kV/cm and 15.0 kJ/kg reduced β-glucan by 38%, and increased malt extract by 1.5%, FAN by 6.2%, and α-amylase by 8.4%, all supporting the hypothesis that PEF treated barley generates more and better quality malt leading to greater efficiency in the beer making process.

The work detailed in the current study demonstrates that PEF technology has significant potential to benefit malt and beer making industries. Batch-size trails were used in this study, but in order for the technology to be adopted by maltsters, continuous flow PEF operations are essential to accommodate the amount of barley requiring treatment. Another possible hurdle for industry adoption is the probable need for multiple PEF systems, on a single line, to reach volume flow-through. PEF system upgrades are ongoing that aim to broaden implementation of the technology into new markets, including malting. The benefits of better-quality malt and shorter germination time is expected to result in higher cost-savings and allow for more malt to be produced. The use of PEF technology may also allow "low" quality grain to be used to produce "quality" malt, and improve low extract yielding grain to potentially meet malt-producing standards.

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CRediT authorship contribution statement

Rose Saxton: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Caitlin Lahey:** Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Brianna Smith:** Validation, Methodology, Investigation, Formal analysis. **Emily Hibberd:** Methodology, Investigation, Formal analysis, Conceptualization. **Joshua Bevan:** Validation, Methodology, Investigation, Conceptualization. **Cini Baumhoff:** Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ashley Galant:** Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Jerry Young:** Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Brian Meyer:** Validation, Supervision, Resources, Methodology, Investigation, Conceptualization. **Owen M. McDougal:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2024.115882.

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