

Comparative Effects of AB Mix and Fish-Emulsion Fertilizer Prepared with Conventional Water or Air-Conditioner Condensate on Hydroponically Grown Caisim (*Brassica rapa* L.)

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Abstract. Air-conditioner condensate water (ACW) and fish-processing residues could provide alternative inputs for hydroponic production, although their compatibility with crop nutrient requirements remains uncertain. This study evaluated the growth and biomass of caisim (*Brassica rapa* L.) supplied with AB Mix or fermented fish emulsion (FE) prepared using tap water (TW) or ACW. Twelve water–nutrient combinations comprising nominal additions of 20, 30, or 40 mL were evaluated alongside a nutrient-free TW control, with five plants per treatment. Plant height, root length, and leaf count were recorded at 7, 14, 21, and 28 days after planting, whereas fresh weight and dry biomass were determined at harvest. Treatment, observation day, and their interaction significantly affected plant height and root length ($P < 0.001$). Leaf count was strongly affected by day and the treatment-by-day interaction, although its overall treatment effect was not significant. AB Mix generally produced greater shoot growth and biomass than FE. TW-AB40 yielded the greatest fresh weight and root length, identifying it as the most suitable formulation when marketable fresh production is prioritized. In contrast, ACW-AB30 produced the greatest dry biomass, indicating that ACW was compatible with effective mineral nutrition and dry-matter accumulation. Further development should focus on standardized mineral–fish-emulsion blends and the integration of ACW into controlled hydroponic nutrient management. Optimization across cultivation cycles may support the practical conversion of condensate water and fish-processing residues into complementary inputs for circular vegetable production.

Keywords: Air-Conditioner Condensate, Fish Emulsion, Nutrient Film Technique.

1 Introduction

Rapid urbanization, declining availability of cultivable land, and increasing pressure on freshwater and fertilizer resources have encouraged the adoption of soilless cultivation for vegetable production. Hydroponic systems provide the solution in which water and mineral nutrients are supplied directly to the root zone and can support intensive crop production within limited areas [1], [2]. Among these systems, the nutrient film technique (NFT) maintains a shallow, continuously circulating nutrient solution around the roots, thereby improving root-zone aeration and allowing water and dissolved nutrients to be reused [3], [4]. These practical designs are superior to leafy vegetables, which have short cultivation periods, high nutrient requirements, and marketable yields that depend strongly on vegetative growth.

Caisim (*Brassica rapa* L.) is widely cultivated and consumed as a leafy vegetable in Indonesia and other Southeast Asian countries. Its short growth cycle and relatively compact canopy make it suitable for urban hydroponic production. At the local scale, hydroponic caisim offers an alternative means of supporting a nearly stable supply of fresh vegetables where agricultural land is increasingly fragmented. Similar concerns at the global level have strengthened interest in controlled-environment and soilless cultivation as resource-efficient approaches to vegetable production [1], [3]. Studies involving *B. rapa* showed that nutrient formulation and rooting medium influence fresh weight, dry biomass, chlorophyll formation, and root development [5], [6]. Therefore, nutrient management remains a principal determinant of crop performance in NFT systems.

AB Mix is widely used for hydroponic leafy vegetables because it supplies readily available macro- and micronutrients while limiting precipitation between concentrated components. These nutrients regulate leaf expansion, chlorophyll formation, root development, osmotic balance, photosynthesis, and enzymatic activity. However, nutrient deficiency restricts growth, whereas excessive concentrations may increase electrical conductivity and osmotic pressure, thereby reducing water and nutrient uptake. Hydroponic nutrient management should therefore account for solution composition, concentration, crop developmental stage, and recirculation period [2]. The growth and fresh yield of leafy vegetables may vary among AB Mix concentrations, with less favorable responses occurring under deficient or excessive nutrient supply [5], [7]. Organic hydroponic nutrients have received increasing attention because recoverable nutrients in agricultural and food-processing residues may reduce dependence on industrially produced mineral fertilizers. However, nutrient release in bioponic solutions depends on microbial decomposition, ammonification, nitrification, oxygen availability, temperature, and pH [8], [9]. Variations in feedstock and fermentation may also cause nutrient imbalance, suspended solids, and elevated biological oxygen demand. Therefore, mineralization, aeration, filtration, or mineral supplementation may be required to achieve nutrient availability comparable with commercial formulations [7]–[9].

Fish-processing residues contain recoverable nutrients that can be converted into liquid fertilizer, thereby reducing organic waste and supporting crop production [10]. Their suitability for hydroponics, however, depends on feedstock composition, fer-

mentation, nutrient amendment, and the mineralization of organically bound nutrients [11]. Fish emulsion and AB Mix are therefore not nutritionally equivalent when applied at equal volumes, requiring dose-based comparisons of plant growth and biomass responses. Water source may further influence nutrient performance. Air-conditioner condensate water (ACW), which is frequently discharged in warm and humid regions, has been evaluated as an alternative irrigation source for hydroponic production [12]. Although its low mineral content may facilitate nutrient adjustment, its agronomic suitability depends on collection conditions, water quality, sanitation, and compatibility with the applied fertilizer.

Mineral nutrients, organic fertilizers, fish-derived inputs, and recovered water have generally been evaluated separately in hydroponic systems [5], [7]–[12]. Hydroponic experiments using aerated animal-manure extracts have also produced source-dependent responses in lettuce and kale, confirming that the effectiveness of organic nutrient solutions is influenced by feedstock composition and nutrient availability [13]. Less attention has been given to nutrient formulations prepared with water sources of different mineral composition, although these combinations may affect solution chemistry, nutrient availability, root conditions, and plant growth. Fresh weight and dry biomass must also be evaluated separately because they represent hydrated yield and accumulated plant matter, respectively.

This study compared AB Mix and fermented fish emulsion at nominal additions of 20, 30, and 40 mL, prepared with tap water or air-conditioner condensate water, for hydroponic caisim cultivation. Plant height, root length, and leaf count were assessed at 7, 14, 21, and 28 days after planting, whereas fresh weight and dry biomass were determined at harvest. Treatment and observation day were evaluated for longitudinal growth responses, while biomass variables were analyzed as treatment-dependent endpoints. The study aimed to determine the effects of water–nutrient combinations on caisim growth and biomass and to assess the potential use of condensate water and fish emulsion as complementary hydroponic inputs.

2 Materials and Method

2.1 Study period and site

The experiment was conducted during April 2026 in the greenhouse of the Biology Laboratory, Faculty of Mathematics and Natural Sciences, Universitas Negeri Medan (UNIMED), Medan, North Sumatra, Indonesia. Following seedling establishment and transfer to the hydroponic system, plant growth was evaluated over a 28-day cultivation period under ambient greenhouse conditions.

2.2 Plant material and hydroponic system

Caisim (*Brassica rapa* L.) seeds were purchased from a local market in Medan City, North Sumatra, Indonesia. The seeds were germinated in 2×2 cm rockwool cubes. The rockwool cubes were moistened uniformly without compression, after which a planting hole approximately 0.5 cm deep was formed in each cube. One seed was

placed in each planting hole. The seedling trays were covered for 1–2 days to maintain moisture during initial germination and were subsequently placed under indirect light. Moisture was maintained by misting when required. Seedlings bearing two to three fully developed true leaves were individually transplanted into net pots installed in a nutrient film technique (NFT) hydroponic system. The system consisted of PVC cultivation channels connected to treatment reservoirs, recirculation pumps, and aeration equipment, following the general configuration of recirculating NFT systems used for leafy vegetable production [4].

2.3 Water sources and nutrient preparation

Two water sources were evaluated: tap water (TW) and air-conditioner condensate water (ACW). Tap water represented the conventional cultivation water, whereas condensate collected from an air-conditioning system was used for the designated ACW treatments. The collected condensate was transferred into clean, closed containers before treatment-solution preparation. A commercial two-component AB Mix fertilizer was used as the mineral nutrient source. Components A and B were prepared and combined according to the general procedure recommended for hydroponic cultivation before being added to the assigned water source. Fish emulsion was prepared from washed and comminuted fish-processing residues fermented with molasses, water, and an EM4 microbial inoculum, following a previously reported fish-waste fermentation procedure with modifications [14]. The mixture was homogenized and incubated in a sealed container at ambient temperature for 21 days. After fermentation, the liquid fraction was separated by filtration and stored in closed containers until use.

2.4 Experimental design and treatments

The experiment consisted of 13 treatments, with five plant replicates assigned to each treatment, with a total of 65 experimental units. Tap water without nutrient supplementation was used as the sole nutrient-free Control. The twelve treatments were arranged as combinations of two water sources, namely TW and ACW; two nutrient formulations, namely AB Mix and FE; and three nominal nutrient additions, namely 20, 30, and 40 mL per treatment solution with the final growing media volume of 500 mL per planting hole (plant). Because an ACW nutrient-free treatment was absent, the complete experimental arrangement was treated as an augmented treatment design rather than a fully balanced factorial design that included both nutrient-free water controls. Each plant was assigned a unique experimental-unit identification code and maintained under its designated treatment throughout the cultivation period as detailed in Table 1. Plant height, root length, and leaf number were evaluated repeatedly on days 7, 14, 21, and 28.

Table 1. Water and nutrient treatments applied during hydroponic cultivation.

Treatment code	Water source	Nutrient source	Volume (mL)	Description
Control	Tap water	None	0	Tap-water nutrient-free control
TW-AB20	Tap water	AB Mix	20	Tap water with 20 mL AB Mix
TW-AB30	Tap water	AB Mix	30	Tap water with 30 mL AB Mix
TW-AB40	Tap water	AB Mix	40	Tap water with 40 mL AB Mix
ACW-AB20	AC condensate	AB Mix	20	AC condensate with 20 mL AB Mix
ACW-AB30	AC condensate	AB Mix	30	AC condensate with 30 mL AB Mix
ACW-AB40	AC condensate	AB Mix	40	AC condensate with 40 mL AB Mix
TW-FE20	Tap water	Fish emulsion	20	Tap water with 20 mL fish emulsion
TW-FE30	Tap water	Fish emulsion	30	Tap water with 30 mL fish emulsion
TW-FE40	Tap water	Fish emulsion	40	Tap water with 40 mL fish emulsion
ACW-FE20	AC condensate	Fish emulsion	20	AC condensate with 20 mL fish emulsion
ACW-FE30	AC condensate	Fish emulsion	30	AC condensate with 30 mL fish emulsion
ACW-FE40	AC condensate	Fish emulsion	40	AC condensate with 40 mL fish emulsion

Note: TW, tap water; ACW, air-conditioner condensate water; AB, commercial AB Mix fertilizer; FE, fermented fish emulsion. The nutrient additions are presented as nominal volumes because the final treatment-solution or reservoir volume was not recorded.

2.5 Treatment-solution preparation and crop maintenance

Each nutrient formulation was added to its designated water source and mixed thoroughly to obtain a homogeneous treatment solution. The prepared solutions were placed in labeled reservoirs and circulated through the NFT cultivation channels. Solution pH and electrical conductivity were monitored (data not recorded) at intervals of 2–3 days only to detect changes in nutrient-solution conditions. Water lost through evaporation, plant uptake, and system operation was replaced whenever required. Treatment solutions were renewed completely every 7–10 days to limit nutrient depletion and excessive changes in solution composition. All plants were maintained within the same greenhouse environment and received similar cultivation and crop-maintenance procedures throughout the experimental period.

2.6 Plant growth measurements

Plant height, root length, leaf number, fresh weight, and dry biomass were selected as indicators of vegetative growth and biomass production commonly used for hydroponically cultivated *B. rapa* [5]. Plant height, root length, and leaf number were recorded for each experimental plant on days 7, 14, 21, and 28 (DAP). Plant height was

expressed in centimetres (cm) and determined from the plant base to the uppermost vegetative point. Root length was also measured in cm from the root base to the tip of the longest observable root. Fully developed and visibly expanded leaves were included in the leaf count. Fresh weight and dry biomass were determined only at the final harvest on day 28. Harvested plant material was drained to remove residual surface solution before fresh weight was recorded using a digital balance. The material was dried until a constant weight was achieved, and the mass was recorded as dry biomass.

2.7 Data analysis

Statistical analyses were performed using Minitab Statistical Software ver. 19.0 at a significance level of $\alpha = 0.05$. Plant height and root length were analyzed using repeated-measures general linear models. Treatment, observation day, and the interaction between treatment and observation day were designated as fixed effects. Experimental-unit identification nested within treatment was included to account for repeated observations from the same plant. Leaf count was treated as a discrete ordinal response. A repeated-measures general linear model was initially used to evaluate the effects of treatment, observation day, and their interaction [15], [16]. For leaf-count data, treatment differences were evaluated separately on each observation day using tie-adjusted Kruskal–Wallis tests. Fresh weight and dry biomass, which were recorded only at the final harvest, were analyzed separately using one-way analysis of variance (ANOVA) across the 13 treatments. Tukey’s HSD test was then applied for pairwise comparisons among all treatments, whereas Dunnett’s test was used to compare each nutrient-supplemented treatment with the nutrient-free Control. The normality and homogeneity of variance assumptions for continuous variables were evaluated using model residuals. Continuous data are presented as the mean $\pm$ standard deviation, whereas leaf-count data are presented as the median and interquartile range. Probability values below 0.001 are reported as $P < 0.001$, while all other values are presented as exact P values.

3 Results

3.1 Longitudinal plant growth

Plant height increased progressively across all treatments from 7 to 28 days after planting (DAP; Figure 1). The repeated-measures model detected effects of treatment and day, together with a treatment-by-day interaction (Table 2), showing that treatment differences changed as plants developed rather than remaining as a constant offset. Differences among treatments were already obvious at 7 DAP but became more significant toward the final observation. TW-AB20 produced the highest mean plant height at 28 DAP (13.44 cm), followed by TW-AB40 (13.00 cm), ACW-AB30 (12.82 cm), ACW-AB40 (12.74 cm), and TW-AB30 (12.48 cm). The fish-emulsion treatments generally produced lower final heights than the AB Mix treatments, with values ranging from 10.36 to 11.10 cm. The nutrient-free Control reached 11.16 cm at

28 DAP. These temporal patterns showed that AB Mix generally supported more rapid shoot elongation, particularly during the later cultivation period.

Root length increased throughout the observation period, although the rate of elongation differed among treatments (Figure 2). Root elongation also depended significantly on treatment, day, and their interaction (Table 2). At 28 DAP, the longest roots were recorded under TW-AB40 (18.98 cm), followed by ACW-AB40 (17.42 cm) and TW-AB30 (16.96 cm). The final root lengths of the fish-emulsion treatments increased consistently with nominal nutrient addition under both water sources. Root length increased from 7.30 cm in TW-FE20 to 15.28 cm in TW-FE40 and from 6.20 cm in ACW-FE20 to 13.86 cm in ACW-FE40. By comparison, the nutrient-free Control produced a final mean root length of 3.62 cm. Thus, root elongation responded more clearly to nutrient dose than plant height, particularly within the fish-emulsion treatments. The summarized plant growth parameters are detailed in Table 3.

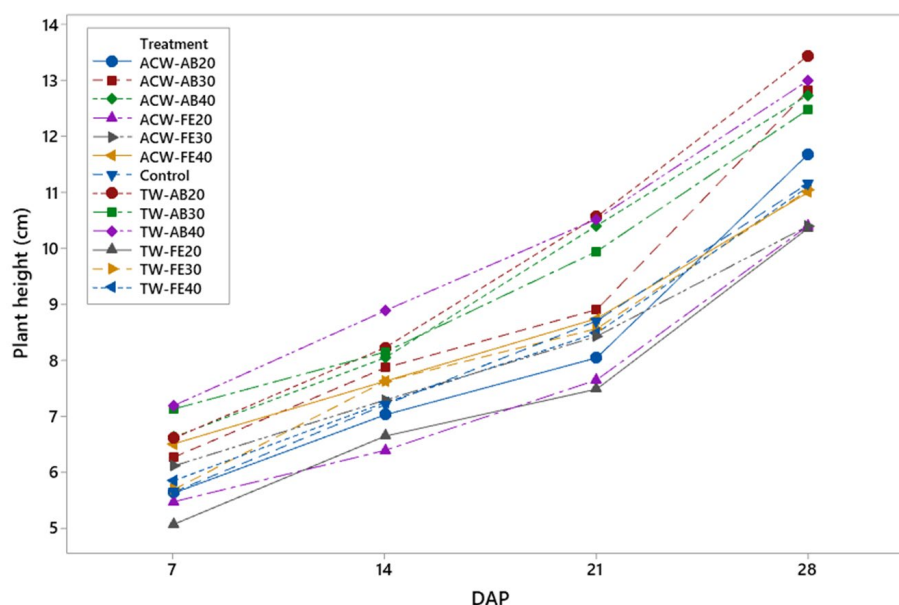


Figure 1. Temporal changes in plant height of hydroponically cultivated caisim under different water sources, nutrient formulations, and nutrient doses. Points represent treatment means at 7, 14, 21, and 28 days after planting (DAP; $n = 5$ plants per treatment).

Table 2. Repeated-measures ANOVA and general linear (GLM) model summary

Response	Term	df	F	P
Plant height	Treatment	12, 52	7.85	<0.001
	Day	3, 156	1845.97	<0.001
	Treatment × Day	36, 156	4.06	<0.001
Root length	Treatment	12, 52	17.05	<0.001
	Day	3, 156	1539.31	<0.001
	Treatment × Day	36, 156	18.01	<0.001
Leaf count ^{a)}	Treatment	12, 52	1.77	0.079
	Day	3, 156	1795.41	<0.001
	Treatment × Day	36, 156	4.72	<0.001

Note: Unit_ID nested within Treatment was included as the plant-level term. ^{a)} The normal-error model for leaf count is an approximation and is supplemented by day-wise tie-adjusted Kruskal–Wallis tests.

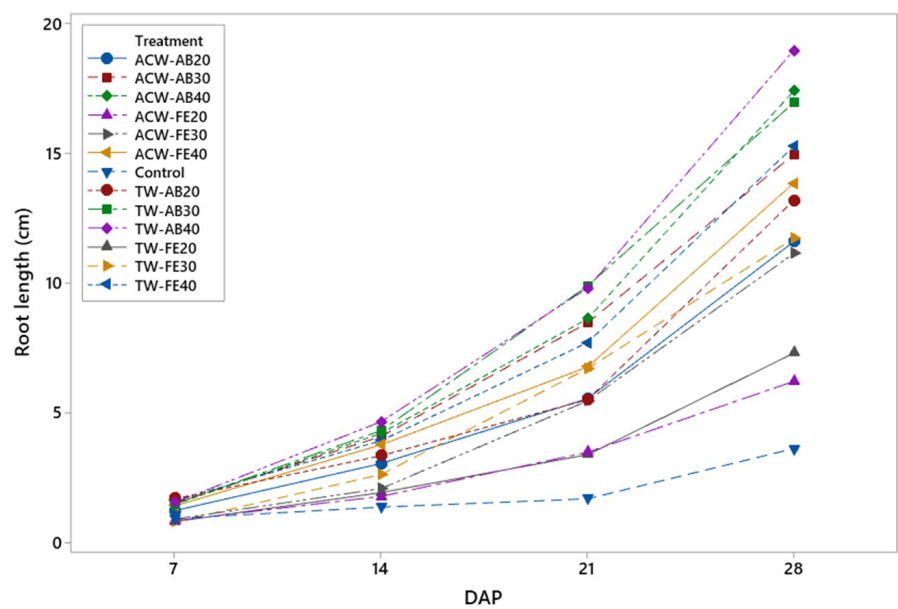


Figure 2. Temporal changes in root length of hydroponically cultivated caisim under different water sources, nutrient formulations, and nutrient doses. Points represent treatment means at 7, 14, 21, and 28 days after planting (DAP; $n = 5$ plants per treatment).

Table 3. Plant performance at the final observation (day 28; *n* = 5 per treatment).

Treatment	Plant height (cm)	Root length (cm)	Leaf count (median, IQR)	Fresh weight (g)	Dry biomass (g)
Control	11.16 ± 1.14	3.62 ± 0.97 e	6 (6–6)	0.074 ± 0.001 h	0.006 ± 0.001 f
TW-AB20	13.44 ± 0.93 a	13.20 ± 2.59 bc	7 (6–7)	0.685 ± 0.016 cd	0.047 ± 0.003 c
TW-AB30	12.48 ± 0.61 abc	16.96 ± 1.93 ab	8 (7–8)	0.743 ± 0.031 bc	0.050 ± 0.002 bc
TW-AB40	13.00 ± 1.17 ab	18.98 ± 3.01 a	7 (7–8)	0.876 ± 0.006 a	0.057 ± 0.002 ab
ACW-AB20	11.68 ± 1.54 abc	11.60 ± 3.71 cd	6 (6–7)	0.672 ± 0.044 d	0.047 ± 0.005 c
ACW-AB30	12.82 ± 0.25 abcd	14.96 ± 2.25 abc	8 (7–8)	0.712 ± 0.021 bcd	0.059 ± 0.003 a
ACW-AB40	12.74 ± 0.53 abc	17.42 ± 2.27 ab	7 (6–7)	0.771 ± 0.047 b	0.054 ± 0.006 abc
TW-FE20	10.36 ± 0.88 d	7.30 ± 1.20 de	6 (6–7)	0.374 ± 0.026 fg	0.022 ± 0.003 de
TW-FE30	11.04 ± 0.90 bcd	11.72 ± 1.19 cd	8 (7–8)	0.402 ± 0.037 ef	0.023 ± 0.003 de
TW-FE40	11.10 ± 1.23 bcd	15.28 ± 3.02 abc	7 (6–7)	0.446 ± 0.005 e	0.028 ± 0.003 d
ACW-FE20	10.40 ± 0.57 d	6.20 ± 1.35 e	6 (6–6)	0.327 ± 0.040 g	0.013 ± 0.003 f
ACW-FE30	10.40 ± 0.67 d	11.14 ± 0.84 cd	7 (6–7)	0.375 ± 0.030 fg	0.021 ± 0.003 e
ACW-FE40	11.00 ± 0.25 cd	13.86 ± 2.53 bc	8 (7–8)	0.420 ± 0.023 ef	0.023 ± 0.004 de

Note: Values are mean ± SD, except leaves, which are median (IQR). Within each column, means sharing a letter do not differ according to Tukey’s HSD test at $\alpha = 0.05$. Bold cells indicate the highest values among data.

3.2 Leaf count response

Leaf number increased numerously within days (DAP; Figure 3). The overall repeated-measures approximation did not detect a treatment main effect ($P = 0.079$), but the treatment-by-day interaction was significant ($P < 0.001$), indicating non-parallel temporal patterns. Day-wise non-parametric tests localized treatment differences to days 14 and 28; no evidence of a treatment effect was detected on days 7 or 21 (Table 4). By day 28, treatment medians ranged from six to eight leaves with the greatest leaf number in four treatments, i.e. TW-AB30, ACW-AB30, TW-FE30, and ACW-FE40 (Table 3).

4 Discussion

Progressive increases in plant height, root length, and leaf number were observed throughout the 28-day cultivation period. However, the significant interactions (treatment×day) for plant height and root length indicated that treatment performance changed during plant development. The differences can be regarded as the cumulative outcome of treatment-specific growth trajectories rather than as constant effects established during early growth. Similar temporal dependence has been reported for hydroponic Brassicaceae, in which nutrient availability, electrical conductivity (EC), and root-zone conditions altered growth rates as nutrient demand increased with plant age [17], [21]–[24]. AB Mix generally supported greater shoot development, root elongation, and harvest biomass than FE. This response may be attributed to the direct availability of nitrate, ammonium, phosphate, potassium, calcium, magnesium, and micronutrients in commercial mineral solutions.

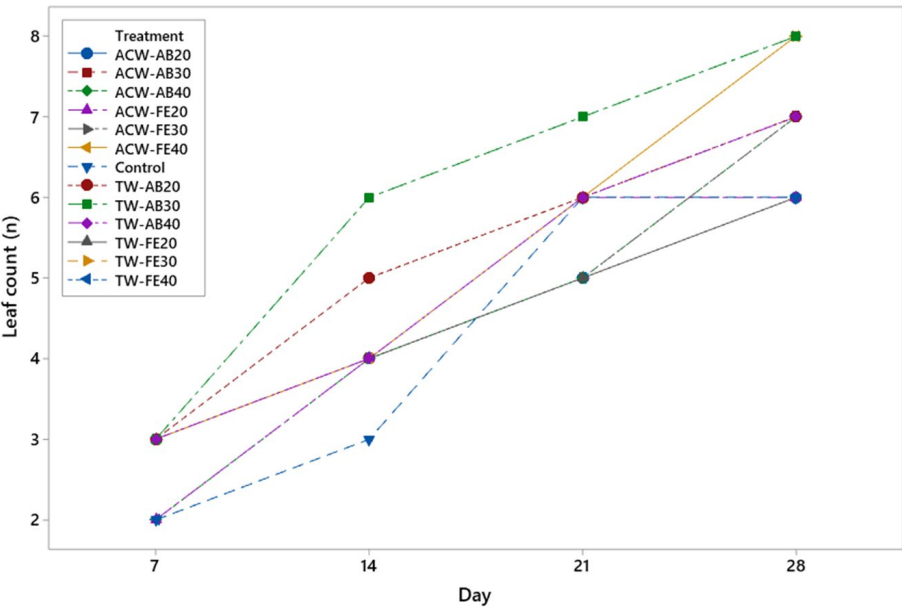


Figure 3. Temporal changes in leaf number of hydroponically cultivated caisim under different water sources, nutrient formulations, and nutrient doses. Points represent treatment median at 7, 14, 21, and 28 days after planting (DAP; $n = 5$ plants per treatment).

Table 4. Day-wise Kruskal–Wallis tests for leaf count.

DAP	Tie-adjusted <i>H</i>	<i>df</i>	<i>P</i>
7	16.64	12	0.164
14	22.52	12	0.032
21	16.90	12	0.154
28	26.37	12	0.009

In contrast, nutrients in fermented organic materials must be released from organic compounds before root uptake can occur. In hydroponically grown bok choy, mineral fertilizer produced greater biomass than several organic formulations when the organic nutrient supply was not sufficiently mineralized [17]. Lower fresh and dry masses have also been reported in lettuce supplied with organic fertilizers derived partly from fermented fish by-products, despite nominally comparable nitrogen application, because nitrogen uptake and nitrogen-use efficiency remained lower than under mineral fertilization [19]. The tallest plants at 28 DAP were obtained with TW-AB20, whereas TW-AB40 produced the longest roots and greatest fresh weight. Plant height was therefore not a sufficient indicator of harvest productivity. Height reflects longitudinal shoot extension, whereas fresh weight is also determined by leaf expansion, tissue water content, stem and petiole development, and root growth. A similar separation among morphological variables has been reported in hydroponic bok choy, for which nutrient formulation affected fresh and dry matter more consistently than individual

vegetative dimensions [17]. The results were also supported by other reports that hydroponic Brassicaceae responded to nutrient strength through coordinated but non-identical changes in shoot morphology, root growth, and biomass accumulation [21], [22].

The effects of the nominal 20, 30, and 40 mL additions were dependent on nutrient formulation and water source. Within the TW-AB Mix treatments, the greatest fresh weight and root length were obtained at 40 mL, indicating that nutrient supply remained favorable at the highest tested addition. However, the greatest dry biomass under ACW was obtained with AB Mix at 30 mL rather than 40 mL. Thus, a higher nominal addition did not consistently maximize every response. Nutrient strength influences plant performance through both nutrient availability and the osmotic properties of the root-zone solution. An insufficient concentration may restrict mineral uptake and leaf development, whereas an excessive concentration can increase osmotic pressure and reduce root water absorption. In hydroponic kale, fresh and dry yield increased across EC values of 1.2–2.1 mS cm⁻¹, whereas collard yield no longer increased above 1.8 mS cm⁻¹, demonstrating that the response to nutrient strength may differ even between closely related Brassicaceae [22]. Pak choi grown under different hydroponic systems also showed system-dependent responses to nutrient-solution EC, with the NFT system requiring a lower EC to reach maximum growth than a semi-hydroponic system [21]. Under tropical raft culture, the greatest pak choi growth was obtained at approximately 2.2 mS cm⁻¹, whereas increasing EC to 2.8 mS cm⁻¹ provided no further yield advantage [24]. These comparisons support the presence of an optimum range rather than an unrestricted benefit from increasing nutrient input.

The treatments that maximized fresh weight and dry biomass differed. TW-AB40 produced the greatest fresh weight, whereas ACW-AB30 produced the greatest dry biomass. Fresh weight includes both accumulated structural matter and tissue water; dry biomass more directly represents assimilated organic matter and retained minerals. The separation between these endpoints suggests that the TW-AB40 treatment favored marketable mass partly through leaf and tissue hydration, whereas ACW-AB30 provided conditions favorable for dry-matter accumulation. Nutrient-solution EC can alter biomass production and tissue hydration simultaneously. Increasing EC may improve nutrient acquisition within an appropriate range, but it can also lower the water potential of the solution and modify tissue water content. Thus, fresh and dry yields do not always respond proportionally to nutrient strength [22], [23].

Fish emulsion did not perform as well as AB Mix, but root length and fresh weight generally increased with dose under both water sources. This pattern indicates that FE supplied nutrients for plant growth, although their availability was probably limited at the lower doses. Fish-derived solutions have also supported hydroponic lettuce, but their effectiveness depended on the concentrations of plant-available nitrogen, phosphorus, potassium, calcium, and micronutrients [20]. The lower performance of FE agrees with previous hydroponic studies. Organic fertilizer produced variable lettuce yields between cultivation cycles, and microbial inoculation did not consistently eliminate the difference from mineral fertilizer [18]. Fermented fish-based fertilizer also produced less shoot biomass when nitrogen uptake and nitrogen-use efficiency were lower than those obtained with mineral nutrition [19]. These

findings indicate that total nutrient content does not necessarily represent the fraction available during a short crop cycle.

Nutrient release from FE depends on microbial mineralization, pH, temperature, aeration, and retention time. Increasing its dose may improve nutrient supply but may also raise ammonium concentration, salinity, suspended solids, and microbial oxygen demand. Organic solutions have achieved yields comparable with conventional hydroponics when nutrient mineralization was adequately managed [27], while parallel mineralization systems have been developed to convert organic materials before supplying them to crops [28]. Improved lettuce growth at higher concentrations of a stabilized organic nutrient product further confirms that dose responses depend on the chemical condition of the final solution [29]. FE may therefore be better developed through aerobic mineralization, filtration, compositional standardization, and selective mineral supplementation rather than through dose escalation alone.

Caisim growth was maintained when ACW was combined with either nutrient formulation. In particular, ACW-AB30 and ACW-AB40 produced plant height and dry biomass comparable with several TW-AB Mix treatments. The low background mineral content commonly associated with condensate may allow the added fertilizer to determine most of the final solution composition. However, condensate quality varies with AC type, cooling-coil material, atmospheric exposure, maintenance practices, drainage, and storage conditions. Recent studies found that AC condensate generally had low EC and dissolved-solids content and could be considered for nonpotable reuse, although chemical quality should be assessed for each collection system [30]. Low concentrations of most dissolved ions and metals have also been reported, but microbial contamination and occasional increases in chemical parameters occurred in some samples [31]. ACW should therefore be characterized before agricultural use. Because an ACW nutrient-free control was absent, the independent effect of water source could not be estimated. The high dry biomass obtained with ACW-AB30 demonstrates compatibility between ACW and mineral nutrition, but not the superiority of ACW over tap water. This distinction requires paired nutrient-free controls for both water sources.

Leaf number increased with plant age, but the overall treatment effect was not significant. Treatment differences occurred only at 14 and 28 DAP, while final medians remained within a narrow range of six to eight leaves. Leaf count was therefore less responsive than plant height, root length, and biomass. Similar outcomes have been reported for hydroponic bok choy, in which nutrient formulation affected biomass and physiological traits more clearly than leaf number [17]. The significant interactions (treatment×day) nevertheless indicates that the timing of leaf development varied among treatments before partly converging at later observations. Our results then support ACW and FE as complementary inputs rather than direct substitutes for conventional hydroponic water and balanced mineral fertilizer. ACW was compatible with nutrient-supplemented caisim cultivation, while the positive FE dose response confirmed that nutrients could be recovered from fermented fish residues. The practical development of FE should prioritize controlled mineralization and partial mineral supplementation.

5 Conclusion

The current findings demonstrate that hydroponic treatment selection depends on the intended production outcome. TW-AB40 was the most appropriate formulation for maximizing marketable fresh yield, whereas ACW-AB30 was preferable for dry-matter accumulation. This distinction indicates that fresh mass alone cannot adequately represent productive efficiency because tissue hydration and accumulated biomass may respond differently to water–nutrient combinations. ACW was compatible with effective caisim production when paired with balanced mineral nutrition, supporting its potential as a supplementary water resource rather than a direct replacement used without quality assessment. Fermented fish emulsion showed agronomic value, particularly for root development, but its performance indicated incomplete or imbalanced nutrient availability relative to AB Mix. Its most promising application may therefore lie in standardized mineral–organic blends. However, these results should be further validated using replicated reservoirs, chemically characterized water and nutrient solutions, equivalent nutrient concentrations, and matched controls for both water sources. Multi-cycle evaluations incorporating nutrient-use efficiency, crop quality, microbial safety, and environmental performance would determine whether these recovered inputs can be incorporated reliably into circular hydroponic production.

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