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RESEARCH ARTICLE

Nitrogen and phosphorus availability from a salmon hydrolyzed fertilizer: A study in controlled conditions

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ABSTRACT

The global tendency of higher production of fish has naturally led to more available derivatives of this industry such as hydrolysates, whose elevated percentage of proteins and mineral nutrients allows them to be used as a fertilization complement in agriculture. One of these products is salmon hydrolysate fertilizer, with unknown fertilizing value. This study determined the dynamics and delivery rate of N and P from a salmon hydrolysate fertilizer produced in Chile. Under controlled laboratory conditions using volcanic soil, a conventional fertilization treatment (urea and triple superphosphate) and control without fertilization were applied. The soil was incubated at 25 °C and 80% of usable humidity at times of 0, 7, 14, 21, 56 and 112 d. The results indicated that the salmon hydrolyzed fertilizer presented a rapid and high N delivery rate (104.2% availability), and its net N delivery value was higher than that obtained with urea. The P applied with salmon hydrolysate presented a high net delivery rate (68.4% availability) compared to triple superphosphate (6.6% availability) but showed erratic delivery dynamics. Soil pH and electrical conductivity were not affected. These results allow us to promote the idea that the use of salmon hydrolyzed fertilizer constitutes a good alternative to the use of conventional fertilizers.

Key words: Salmon hydrolysates, soil fertility, nitrogen, phosphorus, soil incubation.

INTRODUCTION

The food industry produced in aquatic environments has grown in the last decade, registering figures of 179 million tons in 2018 (FAO, 2018; Siddik et al., 2021; Nikoo et al., 2023). The main exporting country of fish and fish products is China with 14% of the registered volume, followed by Norway with 7%, also highlighting India, USA, Canada and Spain (Ahuja et al., 2020). Agricultural production over time has incorporated the use of fertilizer inputs of different nature, which include derivatives from the fish industry in different states of presentation, which occupy from 40%-60% of its initial raw material (Ahuja et al., 2020; Moreno-Hernández et al., 2020; Siddik et al., 2021; Afonso et al., 2022; Nikoo et al., 2023). In general, these products are valued for their protein contribution and their nutritional composition, which in agriculture can be used for direct applications to the soil or in foliar applications (Moreno-Hernández et al., 2020; Afonso et al., 2022; Nikoo et al., 2023). This is a contribution to waste recycling, circular economy, less use of synthetic fertilizers and the energy necessary for their production process, as well as the sustainability of the soil-plant system, thanks to the contribution of C from this type of products (Teutscherova et al., 2017; Nikoo et al., 2023).

The presentation of these products for use in agriculture is normally as hydrolysates, and they are derived from skins, heads, muscles, viscera, bones and eggs (Madende and Hayes, 2020; Siddik et al., 2021; Nikoo et al., 2023). The hydrolysis processes of its proteins and peptides are varied, and the production techniques that ensure higher quality in the final product have more cost (Slizyte et al., 2016; Siddik et al., 2021). When the option is applying directly to the soil, the cost of the equivalent nutritional unit compared to conventional fertilizers is very high, which is why the recommended and used doses are generally low (Ahuja et al., 2020).

After 10 yr of steady growth, in Chile salmon production currently occupies second place following Norway (Cuéllar, 2022). Given the size and importance of Chilean salmon production, the derivatives of this industry have been used as fertilizers in the form of hydrolysates, both for foliar and soil application; however, there are no scientific reports on their effectiveness or fertilizing value. Salmon fish hydrolysate is a fertilizer rich in essential plant nutrients made from fish by-products that have been broken down using an enzymatic hydrolyzed process. The composition of nutrients with fertilizer value of Atlantic salmon (*Salmo salar*) hydrolysates, N, P and Ca stand out with an average of 4.92%, 8.50% and 14.20% dry weight basis, respectively (Ahuja et al., 2020). Considering that in Chile the commercial value of salmon hydrolysates per equivalent unit of nutrient in agriculture is greater than conventional fertilizers, generally the recommended doses for application to the soil fluctuate between 20 and 100 kg or L ha^{-1}, while the foliar application doses correspond to 200 or 300 g or cm^3 100 L^{-1} (Hirzel, 2018; Aminoterra, 2022).

Considering that fertilizers of organic composition such as salmon hydrolysates or other organic fertilizers present a different availability of nutrients than that obtained with conventional fertilizers of inorganic composition, investigation is required to comparatively evaluate their dynamics of delivery or availability of nutrients, as well as delivery rate, with emphasis on N and P given their organic structure (Hartz et al., 2000; Dao, 2004; Hirzel et al., 2019; 2023). In this context, several papers have shown that incubating soils in aerobic conditions with controlled doses of fertilizers, have allowed these questions to be resolved (Hartz et al., 2000; Hirzel et al., 2019; 2023). However, the type of soil in which the study is carried out can also affect both dynamics and rate of delivery of nutrients, mainly N, as well as the soil microflora will generate a decomposition of the carbonaceous fractions to obtain energy through redox reactions. The availability of N will depend on properties of the fertilizer or organic compound such as total N, C:N ratio, total protein molecular C, lignin + biochar molecular C:N ratio, water soluble organic C, acid detergent lignin + extractable alcohol polyphenols/N ratio, water soluble total N, hot water extractable total N, water soluble organic C/water soluble total N ratio, hot water extractable soluble organic C/hot water extractable soluble total N ratio, aromatic C/total N ratio, total N/aryl C ratio, total N/(*O*-aryl C/carbonyl C) ratio, phenolic C/total N ratio, and phenolic C/total organic N (Nett et al., 2010; Eldridge et al., 2017). In order to move forward in gaining knowledge of use of salmon hydrolysates as a source of fertilization, an experiment was carried out with the application of controlled doses of N and P in the form of a salmon hydrolysate and conventional fertilizers (plus a control without fertilization). The hypothesis is that the use of salmon hydrolysate contributes with amounts of N and P equivalent to the use of conventional fertilizers, giving lights as an alternative source of fertilization. The objective of this work was to evaluate the dynamics and delivery rate of N and P with the use of salmon hydrolysate under controlled laboratory conditions.

MATERIALS AND METHODS

Soils

Soil samples were collected from the 0-20 cm depth from an ash-volcanic soil of south-central Chile, a Melanoxerands silt loam (USDA, 2014) from Instituto de Investigaciones Agropecuarias (INIA), Chillán (36°31' S, 71°54' W), Chile. The soil physicochemical characteristics are shown in Table 1. All the chemical properties were analyzed using the methods described by Sadzawka et al. (2006). Soil pH was measured in a 1:2.5 soil:water solution ratio with a pH electrode. Soil organic matter (OM) was determined by the Walkley-Black wet digestion method. Electrical conductivity (EC) was calculated with a conductivity cell (1:5 soil:water ratio). Soil available N ($N\text{-}NH_4^+$ and $N\text{-}NO_3^-$) was extracted with 2 mol L^{-1} KCl and determined by colorimetry in a Skalar autoanalyzer (segmented flux spectrophotometer) (Skalar Ltd., York, UK). Available P in the soil sample was extracted with 0.5 M $NaHCO_3$ and determined with ascorbic acid-molybdate. Exchangeable Ca, Mg, K, and Na were determined by 1 M ammonium acetate extraction followed by flame spectroscopy, that is, absorption (Ca and Mg) and emission (K and Na). Soil exchangeable Al concentration was determined by 1 M KCl extraction with absorption spectroscopy. Soil Fe, Mn, Zn, and Cu concentrations were determined in diethylenetriaminepentaacetic acid (DTPA) extract by atomic absorption spectrometry (AAS). Boron (B) was determined by colorimetry in a solution obtained after hot water extraction. Soil available S was extracted with calcium phosphate and determined by turbidimetry. Soil texture was analyzed by the Bouyoucos method with a hydrometer. Bulk density was determined by the cylinder method on five cores from each soil.

Table 1. Chemical and physical properties of the soils used in the experiment.

Soil property	Ash volcanic soil
Clay, %	15.2
Silt, %	42.3
Sand, %	42.5
Water retention 33 kPa, %	34.6
Water retention 1500 kPa, %	18.7
pH 1:5 soil:water	6.16
Organic matter, g kg^{-1}	112.3
Available N, mg kg^{-1}	35.3
Available P, mg kg^{-1}	25.6
Exchangeable Ca, $cmol_+$ kg^{-1}	4.7
Exchangeable Mg, $cmol_+$ kg^{-1}	0.45
Exchangeable K, $cmol_+$ kg^{-1}	0.96
Exchangeable Na, $cmol_+$ kg^{-1}	0.11
Exchangeable Al, $cmol_+$ kg^{-1}	0.01
Effective exchangeable cation capacity, $cmol_+$ kg^{-1}	6.23
Available S, mg kg^{-1}	18.1
Available Fe, mg kg^{-1}	34.7
Available Mn, mg kg^{-1}	3.2
Available Zn, mg kg^{-1}	0.7
Available Cu, mg kg^{-1}	0.3
Available B, mg kg^{-1}	0.4

Fertilization treatments

Three fertilization treatments were evaluated: 1) Control without fertilization as an indicator of soil nutrient supply; 2) salmon hydrolysate (granules) generated for the industry of process of fish residues (Landes, Talcahuano, Chile), produced through enzymatic hydrolysis generating smaller peptides, which improves its functionality as a fertilizer, in rates of 2.775 mg kg^{-1} N and 0.65 mg kg^{-1} P, corresponding to a rate of 50 kg ha^{-1} as recommendation of use in agriculture; and 3) conventional fertilizers with use of urea and triple super phosphate in rates of 100 mg kg^{-1} N and 50 mg kg^{-1} P. The chemical characteristics of the salmon hydrolysates are presented in the Table 2, and were analyzed at the INIA Laboratory following standard procedures (Methods of Soil Analysis, 1996).

Table 2. Chemical properties of the fertilizers used in the experiment and rate of N and P used of each one. [nd]Not determined.

Parameter	Urea	Triple super phosphate	Salmon hydrolysate fertilizer
pH	nd	nd	6.15
Total N, %	46.0	-	11.1
C:N ratio	0.43	-	0.54
$N\text{-}NH_4^+$, mg kg^{-1}	-	-	1658.2
$N\text{-}NO_3$, mg kg^{-1}	-	-	0.01
Total P, %	-	20.1	2.60
Total K, %	-	-	0.63
Total Ca, %	-	15.0	4.63
Total Mg, %	-	-	0.19
Total Na, %	-	-	0.90
N rate, mg kg^{-1}	100.0	-	2.775
P rate, mg kg^{-1}	-	100.0	0.65
K rate, mg kg^{-1}	-	-	0.1575

Soil incubation

All the fertilizers (granules) were ground with mortar and pestle (< 60 mesh), which probably increased its real N availability for testing under controlled conditions for a limited period of time. Samples of individually homogenized soils (100 g) were placed in 0.25 L plastic jars. The rate use for salmon hydrolysate was 0.025 g jar^{-1} and for urea and triple super phosphate were 0.222 and 0.109 g jar^{-1} respectively. Fertilizers were then individually applied and mixed with the soil samples, moistened to 80% of their water holding capacity, and incubated aerobically at 25 ± 2 °C in a refrigerated incubator (FOC 225E, Velp Scientifica, Usmate, Italy) for 16 wk. The jars were left uncovered for 1 h and soil moisture was adjusted gravimetrically every week (Hirzel et al., 2019). At each sampling date (0, 7, 14, 21, 56, and 112 d), three replicates of each fertilization treatment were randomly selected to analyze pH, electrical conductivity (EC), available P, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$ and inorganic N (sum of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$). Analyses of $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ were performed in a Skalar autoanalyzer (segmented flux spectrophotometer) (Skalar Ltd.) using 5 g soil sample. In addition, pH, EC, and available P were determined with the previously described soil analysis methodologies.

Determination of N availability rate and dynamics

The N availability rate was calculated as the sum of the concentration of $N\text{-}NH_4^+$ + $N\text{-}NO_3^-$ of the whole incubation time to determine inorganic N for the whole incubation period minus the inorganic N concentration of the control without fertilization, divided by the amount of total N applied at the start of the experiment (100 mg kg^{-1} in the conventional fertilization and 2,775 mg kg^{-1} in the salmon hydrolysate) and then multiplied by 100 to express the result as a percentage (Equation 1):

$$\text{N availability rate (\%)} = [(N_f - N_c)/100] \times 100 \qquad (1)$$

where N_f is the average concentration of inorganic N of a fertilization treatment and N_c is the average concentration of inorganic N of the control treatment. At the same time the P availability rate in each incubation time was calculated with the Equation 2.

$$\text{P availability rate (\%)} = [(P_f - P_c)/100] \times 100 \qquad (2)$$

Using the N availability rate, obtained as an average of the whole incubation period, treatments were arbitrarily rated as low (less than 30%), moderate (between 31% and 60%), or high (greater than 61%) N availability fertilizers (Hirzel et al., 2019). The aim was to facilitate the selection of an N-based fertilizer and its application rate for certain crop development stages, which were based on this parameter.

The dynamics of N availability was determined as the sum of $N\text{-}NH_4^+$ + $N\text{-}NO_3^-$ at each evaluation time (0, 7, 21, 56, and 112 d). The fertilization treatments were arbitrarily classified as slowly, moderately, or rapidly available N fertilizers according to their percentage of N availability reached during the first 7 and 28 d incubation. Therefore, treatments with an N availability rate greater than 60% at 7 d incubation were classified as rapidly available fertilizers, while fertilization treatments at an N availability rate greater than 60% at 28 d incubation were classified as moderately available, and treatments with an N availability rate less than 60% after 28 d incubation were classified as a slowly available fertilizer (Hirzel et al., 2019).

Statistical analysis

The experimental design was a split-plot design in which incubation time was the main plot and the fertilization treatment was the subplot. One- and two-way ANOVAs and the mean separation test (Tukey) were performed at the 5% significance level using SAS 8.0 (SAS Institute, Cary, North Carolina, USA). Contrast analysis was used to separate the interactions that were obtained.

RESULTS

The soil used did not present fertility limitations that could affect the activity of the soil biomass and thus the rate of mineralization and delivery of N and P, mainly considering the contents of organic matter and concentration of available N, P and S (Table 1). The evaluated fertilizer presented a low C/N ratio and high N/P ratio in relation to other organic fertilizers such as compost from different origins (Table 2).

Incubation time had highly significant effects and so did fertilization treatment and the interaction of both sources of variation for all the parameters evaluated, except for the interaction obtained in available N (data not showed). These interactions could indicate that the quantitative differences between treatments for the evaluated parameters will present different magnitudes, depending on the incubation time (Figures 1 to 8).

The evolution of soil pH (Figure 1) showed a cumulative drop throughout the evaluation period, with a greater magnitude during the first 21 d incubation in control and hydrolysate treatments, and first 56 d incubation for the conventional fertilization. The highest pH during large part of the incubation period was achieved in the treatments with hydrolysates and control ($p < 0.05$), and the lowest value was obtained with conventional fertilization. The EC presented a different behavior than pH (Figure 2), showing a gradual increase in the three treatments during the incubation period, with a greater magnitude of change in the control and treatment with hydrolysate during the first 21 d incubation. The treatment with conventional fertilization presented a large magnitude of change during the first 56 d incubation. The highest EC was obtained in the treatment with conventional fertilization ($p < 0.05$), with no differences between the other 2 ($p > 0.05$).

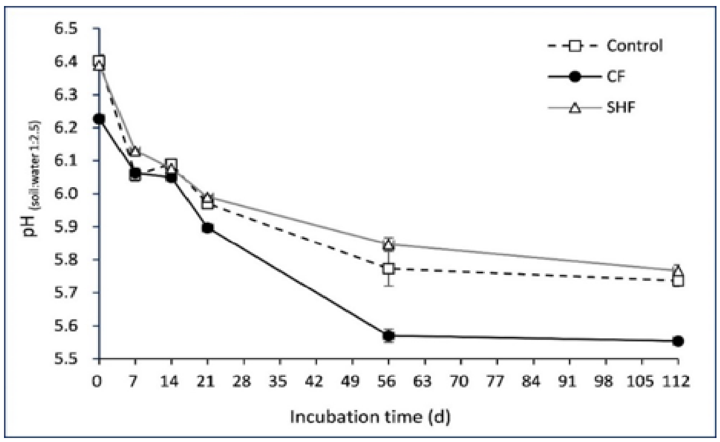

Figure 1. Evolution of the pH in the soil during the incubation period. Lines over the values of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

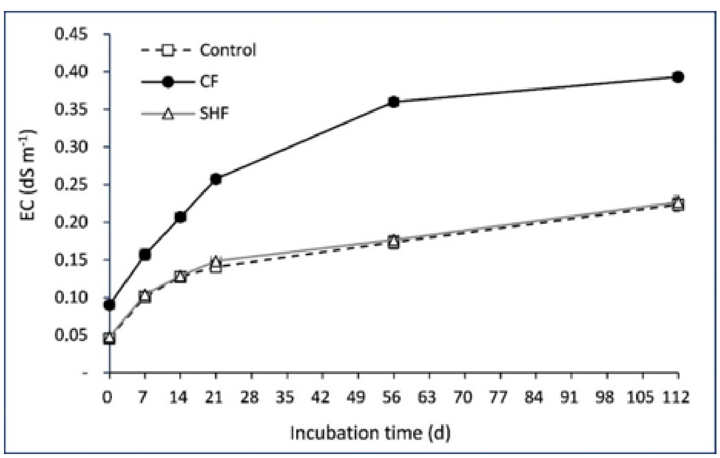

Figure 2. Evolution of the electrical conductivity (EC) in the soil during the incubation period. Lines over the values of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

The available ammonium (Figure 3) presented its highest concentration at the beginning of the incubation period, with a rapid drop until 21 d incubation in the control and hydrolysate application treatments, while with conventional fertilization this drop was observed until 56 d incubation, without subsequent changes and with low concentration until the end of the soil incubation period. The highest concentration of ammonium during the first 21 d incubation ($p < 0.05$) was obtained in the conventional fertilization treatment, associated with highest dose of N applied (Table 2). The nitrate concentration (Figure 4) showed a continuous increase throughout incubation, with a greater magnitude up to 21 d incubation in the control and hydrolysate treatments, and up to 56 d in conventional fertilization. The highest nitrate concentration was obtained with conventional fertilization from day 14 onwards ($p < 0.05$), possibly associated to the dose of N used in the conventional fertilization treatment, similar for ammonium (Table 2). The availability of N (ammonium + nitrate) (Figure 5) presented a constant increase throughout the soil incubation time, with a greater magnitude during the first 7 d in the control and hydrolysate treatments, and during the first 14 d with conventional fertilization. Consistently, the highest concentration of available N was achieved with conventional fertilization throughout the incubation period ($p < 0.05$), associated with the highest dose of N used compared to the hydrolysate treatment (Table 2).

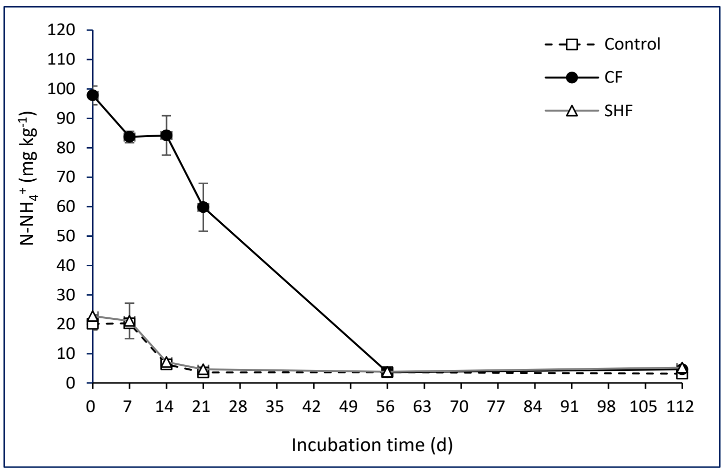

Figure 3. Evolution of the $N\text{-}NH_4^+$ concentration in the soil during the incubation period. The lines over the values of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

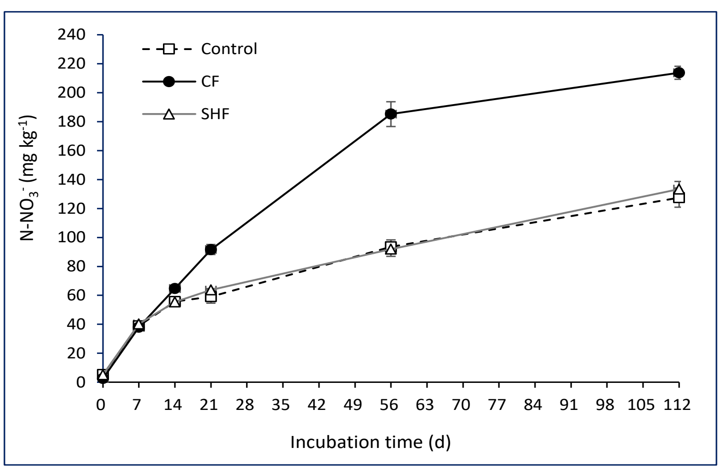

Figure 4. Evolution of the $N\text{-}NO_3^-$ concentration in the soil during the incubation period. The lines over the values of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

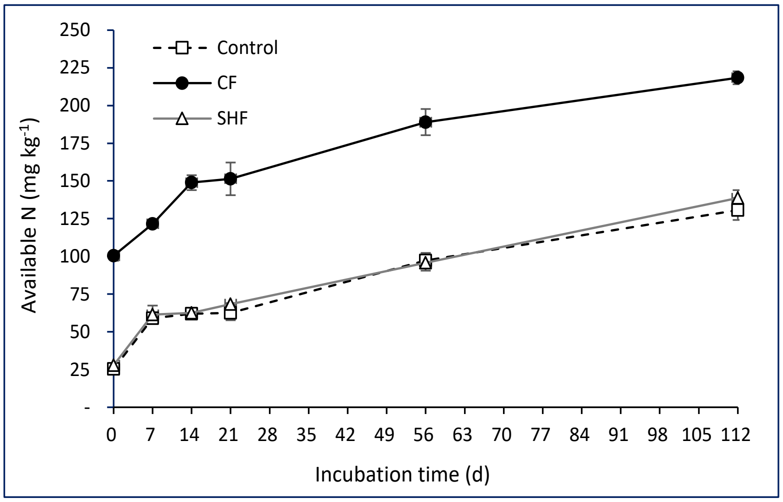

Figure 5. Evolution of the N availability ($N-NH_4^+ + N-NO_3^-$) in the soil during the incubation period. The lines over the values of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

The availability of P showed erratic effects (Figure 6), with differences in behavior between treatments for certain incubation times. On day 7, the control showed a drop (1.9 mg kg^{-1} compared to the initial value) and slightly increased up to day 56, with a new drop until the end of the incubation period. The treatment with hydrolysate presented a similar behavior to the control, but the decrease in concentration on day 7 was smaller (1.1 mg kg^{-1} compared to the initial value). The hydrolysate treatment was only higher than the control at 0 and 7 d ($p < 0.05$), showing a lower concentration than the control at 56 d ($p < 0.05$). For its part, conventional fertilization presented a consistent drop in the concentration of P from the beginning of the incubation period until day 14, and then presented a slight increase until day 56, and subsequently decreased again obtaining the lowest value for this treatment throughout the soil incubation period (8.2 mg kg^{-1} decrease on day 112 compared to the initial value). As expected, the highest concentration of available P was consistently obtained in the treatment with conventional fertilization, considering that the dose of P used was 153.8 times higher compared to the treatment with salmon hydrolysate (Table 2).

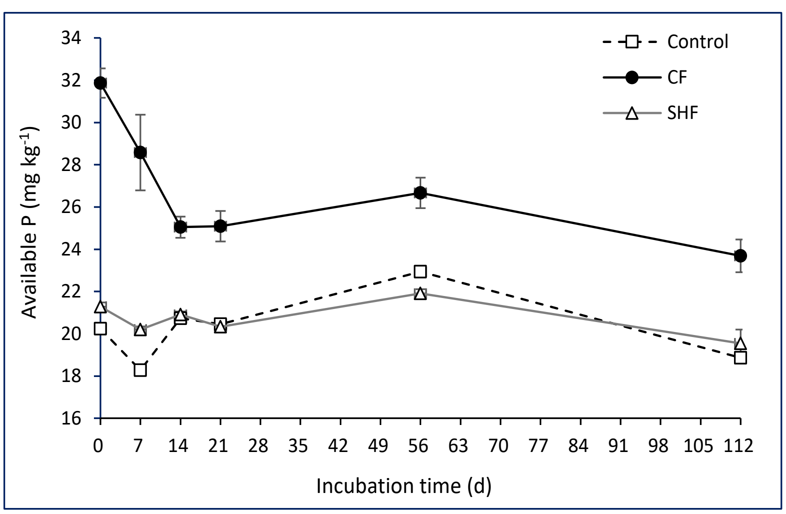

Figure 6. Evolution of the P concentration in the soil during the incubation period. The lines over the values of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

The N availability rate (Figure 7) in the treatments fertilized with this element presented erratic effects during the incubation period that were much more noticeable in the treatment with hydrolysate. Under conventional fertilization, a drop was observed on day 7 of incubation, probably associated to immobilization processes. An increase on day 14 kept stable during the remaining incubation period, having an availability rate of less than 100% during the entire incubation period. The treatment with hydrolysate presented a slight decrease in the availability rate on day 7, then increased until day 14, exceeding the 100% availability rate, and decreased again until day 56, with a marked increase from day 56 to the end, achieving a 186.7% N availability rate. The changes observed in the N availability rate for the hydrolysate treatment could indicate a higher dynamic between immobilization processes of net N mineralization, with a "primming" effect during some stages of the soil incubation period. Comparing N availability rate with hydrolysate, it was higher than with conventional fertilization in most of the soil incubation period ($p < 0.05$). Given that the N availability rate in the hydrolysate was greater than 60% at 7 d incubation (Figure 7), this fertilizer can be classified as having rapid N availability. Considering the average value of the incubation period (Table 3), the highest net N availability rate was achieved with hydrolysate, being 1.27 times higher than the value obtained with conventional fertilization, also reaching an availability rate greater than 100%, which allows this fertilizer to be classified as having high N availability.

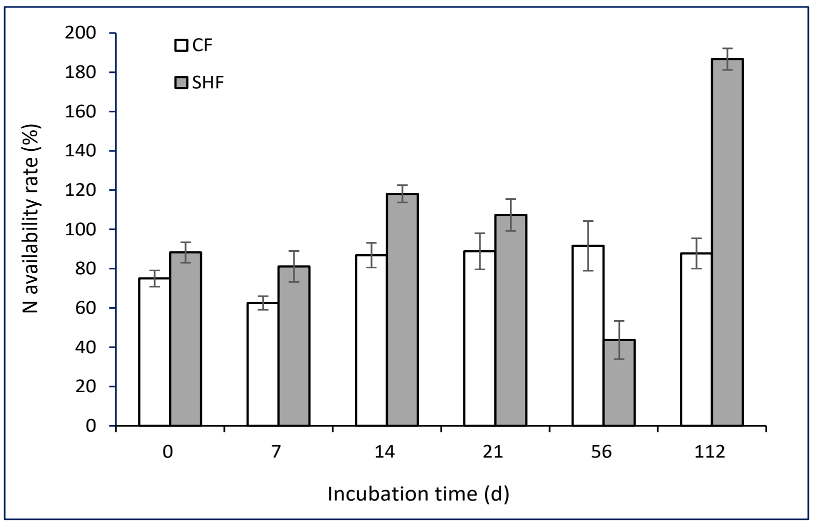

Figure 7. Evolution of the N availability rate in the soil during the incubation period. The lines over the bars of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

Table 3. Nitrogen and phosphorous availability rate of the treatments evaluates as average of the time of evaluation. Different letters in the same row indicate significant differences between treatments according to Tukey's test ($p < 0.05$). Values are ± standard error.

Treatment	Availability rate (%)	
	N	P
Conventional fertilization	82.1 ± 7.2^b	6.6 ± 0.8^b
Salmon hydrolysate fertilizer	104.2 ± 6.8^a	68.4 ± 4.8^a
Significative minimum difference	6.22	5.34

The P availability rate (Figure 8) presented a different behavior, with a very stable value in conventional fertilization during most of the incubation period, and with a strong decrease in the first 21 d with hydrolysate, to then achieve an increase from day 56 to the end of the incubation period. In both treatments, the highest value of P availability was recorded at the beginning of the incubation time, as expected in this soil of volcanic origin and which indicates P fixation processes during the time close to the time of application of both fertilizers with contribution of P. However, using hydrolysate, an increase in availability was observed in the final phase, which was not expected for the application of P in this type of soil. Finally, the P availability rate was higher with hydrolysate in most incubation times ($p < 0.05$). When considering the average value of the incubation period (Table 3), and as what was observed for N, the highest rate of net availability of P was achieved in the treatment with hydrolysate, being 10 times higher than the value obtained with conventional fertilization and achieving an availability rate greater than 60%.

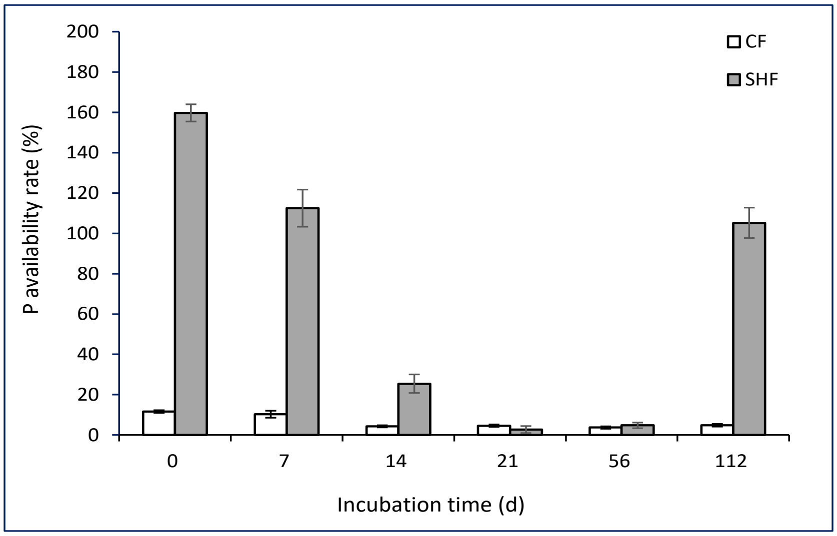

Figure 8. Evolution of the P availability rate in the soil during the incubation period. The lines over the bars of each incubation time indicate the standard error. CF: Conventional fertilizers; SHF: salmon hydrolysate fertilizer.

DISCUSSION

Obtaining interactions between incubation times and fertilization treatments is very common for incubation experiments as seen in previous studies (Hirzel et al., 2019; Paillat et al., 2020; Hirzel et al., 2023), and could be explained by the effect of temperature, humidity and oxygen on soil biomass activity during the incubation period, generating changes in magnitude in the concentration of nutrients released from soil reserves, as well as from organic fractions and chemicals present in the applied fertilizers (Hartz et al., 2000; Dao, 2004; Hirzel et al., 2019; 2023).

The decrease in soil pH during incubation process is generated by the release of acid reaction compounds associated with the microbial activity of the soil, highlighting carboxylic acids, release of CO_2 by respiration that is then conjugated with soil water to form acid CO_2, as well as by the release of protons derived from the N nitrification process (Havlin et al., 2016; Hirzel et al., 2019; 2023). The pH differences obtained between treatments can be explained by their composition, highlighting the presence of basic reaction cations in the hydrolysate, as well as by the magnitude of the N applied with each treatment, and which is then nitrified in the soil (Pansu and Thuriès, 2003; Havlin et al., 2016; Wang et al., 2023). Likewise, the increase in EC obtained during the soil incubation period is generated by the contribution of nutrients in each treatment, as well as by the mineralization of nutrients from the organic fraction of the soil and release of nutrients from soil ion exchange sites (Hartz et al., 2000; Havlin et al., 2016; Teutscherova et al., 2017). The higher EC obtained with conventional fertilization is explained by the higher dose of nutrients used with this treatment. Effects on soil pH and EC such as those obtained in this experiment, has been reported before by Paillat et al. (2020) in incubation experiments with organic fertilizers.

The application of ammonia sources with hydrolysate and conventional fertilization generated a high concentration of ammonia at the beginning of incubation, which then begins to nitrify, as is normal in aerobic incubation processes (Hartz et al., 2000; Hirzel et al., 2019). On the other hand, the N mineralization observed in this soil was high compared to that obtained in non-volcanic soils (Hirzel et al., 2019; 2023) and is explained by several factors; high soil organic matter content, greater aerobic biomass activity associated with this organic matter, soil incubation conditions, and low C/N ratio of the fertilizers used (Nett et al., 2010; Havlin et al., 2016; Eldridge et al., 2017). The higher concentration of ammonium and then nitrate, as well as available N (ammonium + nitrate), obtained with conventional fertilization is explained by the higher dose of N.

In relation to the availability of P during soil incubation, an intense fixation was observed in conventional fertilization treatment during the first 14 d, which was expected given the presence of amorphous clays and the structural Al of the clays in this volcanic soil (Chatterjee et al., 2014; Havlin et al., 2016). The decrease in the concentration of P after 7 d incubation in both the control and the hydrolysate can be explained by chemical reactions between Ca-P, Mg-P, and Fe-P, especially in this soil with high concentration of Fe, as seen before (Chatterjee et al., 2014; Havlin et al., 2016). However, the mineralization processes of the organic P present in the soil contributed to the increase in P availability until day 56, without an additional effect on the increase in P concentration with the application of hydrolysate compared to the control, probably due to the low dose used as well as the high Ca/P ratio of this fertilizer (1.78). This could generate chemical reactions of P fixation (Havlin et al., 2016), or possible formations of organic P as non-labile phospholipids, inositol, and orthophosphate diesters in soils with high microbial activity, which are more resistant to degradation (Dao, 2004; Verma et al., 2005; Silveira et al., 2006).

All treatments presented a decrease in P concentration from day 56 to 112, probably associated with the decrease in the delivery of P from the organic and chemical reserves of the soil, as well as the P provided by fertilizers, compared to P fixation processes of constant intensity during that period of time (Chatterjee et al., 2014; Havlin et al., 2016). A greater availability of P was expected with conventional fertilization compared to hydrolysate, given the relative difference in the doses used with each product (153.8 times greater with the use of conventional fertilizer). Even though it has been described that the application of organic fertilization allows an increase of the soil enzymatic activities of acid phosphatase, alkaline phosphatase, with an increase in P availability in the soil (Cardarelli et al., 2023), this effect was not observed in our experiment given the low dose of P applied through the hydrolysate.

The relative rate of N delivery with the use of conventional fertilization (urea) was stable throughout the incubation period, which was expected given the rapid delivery of N from this fertilizer, achieving peak delivery normally 14 d later after the incubation has started (Hirzel et al., 2019; 2023). The drop observed in the N availability rate in both treatments with fertilization on day 7 of incubation is explained by net N immobilization processes, especially when a rapid release of C occurs from fertilizers with a low C/N ratio and presence of low molecular weight carbon compounds such as those used in this experiment (Hartz et al., 2000; Wang et al., 2015; Havlin et al., 2016; Eldridge et al., 2017). This effect can be considered as a suitable indicator of biological activity and living soil, and as a tool to assess biological activity in soils under organic or integrated sustainable management.

The effect obtained in the relative rate of N delivery from day 21 to 56 and after 56 d with the application of hydrolysate is outstanding, which shows a greater immobilization of N from day 21 to 56, and then an increase in mineralization until the end of the incubation period. This effect can be explained by the organic composition of the C and N of the hydrolysate, with compounds that stimulate constant growth of microbial biomass or C:N imbalance (net immobilization), and subsequently compounds with less stimulation of the growth of microbial biomass or greater activity enzymatic activity associated with N mineralization, which in turn allows greater net delivery of N (net mineralization) (Havlin et al., 2016; Eldridge et al., 2017; Dalias and Christou, 2022; Wang et al., 2023), however, in this study a qualitative and quantitative description of the compounds with C and N of the hydrolysate was not considered, nor were specific measurements of biological activity, such as respiration or other. Effects of net immobilization and then net mineralization have been described in soil incubation experiments for 180 d with the aggregation of different organic materials of different C/N ratio and composition of organic molecules, such as olive pulp, coffee cake, wet grape berry pellicle cake and dry grape berry pellicle cake (Pansu and Thuriès, 2003).

Dalias and Christou (2022) have also described continuous immobilization-mineralization-immobilization processes of N determined in soil incubation experiments for different organic compounds used as a fertilization source. On the other hand, the relative N delivery rate values greater than 100% achieved with the application of hydrolysate indicate a “primming” effect on the mineralization of native N in the soil, which has been described for other products or fertilizers with contribution of N (Wang et al., 2015; Havlin et al., 2016). The high N availability value and the high net N delivery rate obtained with the salmon hydrolysate evaluated allows it to be considered as a suitable alternative to the use of conventional fertilizers with rapid N delivery (Hirzel et al., 2019).

In relation to the relative P delivery rate, as expected for conventional fertilizer, an almost constant value was obtained during the soil incubation period, associated with the P fixation processes in the soil, which occurs mainly during the first days after the fertilizer application (Hirzel et al., 2010; Chatterjee et al., 2014; Havlin et al., 2016). In the case of hydrolysate, this fixation effect was also observed during the first 21 d incubation. However, the increase obtained from day 56 to 112 indicates P release processes from the fertilizer or from soil reserves, which could be stimulated by the quality of the organic compounds present in the hydrolysate and its stimulating effect on the enzymatic activity in the soil, which allowed increasing the availability of P (Cardarelli et al., 2023; Paillat et al., 2020). However, this study did not consider characterization of the organic compounds present in salmon hydrolysate, nor evaluations of biological or enzymatic activity in the soil.

Finally, further complementary studies with use of salmon hydrolyzed fertilizer in field conditions with biological indicators of high nutrient demand should be conducted.

CONCLUSIONS

This soil incubation study in this volcanic soil allowed us preliminarily to determine that the use of salmon hydrolyzed fertilizer presents a rapid and high rate of N delivery, with a net N delivery value greater than that obtained with the use of urea. For P, the delivery dynamics were erratic during the incubation period, but its delivery rate was higher than that obtained with the use of triple superphosphate. Other chemical soil properties indicative of chemical fertility such as pH and EC were not affected by the use of salmon hydrolyzed fertilizer at the evaluated dose. These preliminary results under controlled conditions allows suggest that the use of salmon hydrolyzed fertilizer constitutes an alternative to the use of conventional fertilizers.

Author contributions

Conceptualization: J.H., L.I. Methodology: J.H., L.I. Software: J.H. Validation: J.H. Formal analysis: J.H. Investigation: J.H., L.I. Resources: J.H., L.I. Data curation: J.H. Writing-original draft: J.H. Writing-review & editing: J.H. Visualization: J.H. Supervision: J.H. Project administration: J.H., L.I. Funding acquisition: J.H., L.I. All co-authors reviewed the final version and approved the manuscript before submission.

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