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Growth and nitrogen recovery efficiency of potato (*Solanum tuberosum*) fertilized with shrimp shell pellets

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Acknowledgements

This study is part of a project owned by the producers' organization OTTAR (contact: Halgeir Jakobsen), with Stella Polaris AS (contact: Jaran Rauø) as project participant (Project no. 182724 in The Research Council of Norway). Thanks to a previous employee in NIBIO, Christian Uhlig, for contribution to planning of the experimental set-up.

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Abstract

In organic plant production, nitrogen (N) availability is often a growth-limiting factor. Under such conditions, off-farm waste-derived nutrient resources may be an alternative to meet the N demand. In this study, we described a production method for a shrimp shell (SS) pellet product and evaluated the N fertiliser effect and N recovery efficiency (NRE) in a controlled climate pot experiment with potatoes. The experiment was set up with low, medium and high N levels of SS pellets in comparison with a standard mineral fertilizer (MF) at 9, 15 and 21°C. In a separate study, we examined the loss of N as N_2O from SS pellets in comparison with SS powder in a 100 days incubation experiment. The results documented the possibility to formulate a fertilizer pellet product from SS, and that SS pellets were an effective N fertilizer in potato at all growth temperatures. Nevertheless, a slightly slower development and lower tuber yields than for MF indicated a delayed N-availability from SS pellet fertilizer. NRE after use of MF was around 90%, and about 70% for the different levels of SS pellets. The incubation experiment showed a higher rate of available N for SS powder than for pellets (67% and 39%, respectively) after 100 days of incubation at constant humidity and temperature. This difference was attributed to a lower degree of dissolved materials and a higher rate of denitrification and N_2O emissions for pellets than for powder, probably caused by differences in physical properties, occurrence of anoxic hotspots and higher microbial activity around and inside the SS pellets.

Key words: controlled climate; extrusion; nitrogen mineralization; nitrous gas emission; pelletizing; waste-derived fertilizers.

Introduction

In organic plant production, nitrogen (N) availability is a growth-limiting factor, especially on stockless farms without animal manure and in cold climates with reduced decomposition of green manure and limited N-fixation by legumes. Under such growing conditions, there is often a need for off-farm nutrient resources to meet the N demand. In northern areas, there has been a special attention to utilizing marine waste-derived organic materials as fertilizers (Ytreberg 1959; Bjøru 1996). Such slaughter residues are generally rich in nutrients and energy, and constituted about 914 000 Mg in Norway in 2016 (Richardsen et al. 2017). Shellfish (mainly shrimp shell) constituted about 12 000 Mg, of which about 29% was utilized as fish fodder meal, chitin/chitosan production, cosmetics, etc.

In 2003-2005, the growers association 'Ottar' in Northern-Norway, initiated several studies on the fertilizer effect of both fresh shrimp shell (SS) and dried SS powder in greenhouse and field experiments with potatoes (Tor J. Johansen, unpublished). Chemical analyses showed that these products had a wide and relatively balanced nutrient content related to potato requirements, except for a minimal content of potassium (K). However, with supplements of K, the growth responses were comparable to the use of mineral fertilizer (MF), though with a slightly delayed N availability for fresh shells in the field experiments.

Use of fresh SS and SS powder have limited relevance for commercial use due to challenges within transport, storage and application. This management problem can be solved by processing the SS powder into pellets by use of pelletizing or extrusion technology; production methods extensively used in feed and food manufacturing. In a pelletizing process, a moistened and heated material is compacted and shaped through die holes into pellets and dried (Thomas et al. 1997). Extrusion is a process that transforms the material into a high viscous flowable mass controlled by water and steam injection and viscous heat dissipation in one or two screws. The material is then shaped through dies, cut into pellets and dried (Riaz 2000). Extruded pellets generally have higher physical quality and produce less fine particles than at pelletizing. However, the durability of the final product from both processes is dependent on technical properties of the protein components and normally improved by the addition of starch and other binders (Thomas et al. 1998; Samuelsen et al. 2013; Samuelsen and Oterhals 2016).

In 2007, the grower's association 'Ottar' initiated a new project (2007-2010), including a test-production of SS pellet products and further studies of workability and fertilizer effects in field and controlled climate chambers. In an adjoining research project the chosen pellet product was tested for its effects on yield, N-contents and quality, in a field study with broccoli, potato and lettuce (Øvsthus et al. 2015, 2017). Results indicated adequate N mineralization and effects as N fertilizer. In addition, Øvsthus et al. (2017) investigated the N-recovery efficiency (NRE, also called N-use efficiency, NUE) for the SS pellets. For potato, yields at estimated available N-levels of 80 kg ha^{-1} for the SS pellets, did not differ significantly from the similar N-level of MF, and the NRE was close to 50% for SS pellets in field, compared to around 60% for MF. The authors also showed that residuals of inorganic N in soil were at moderate or un-detectable levels, and did not differ between fertilizers at the end of season.

Before using these waste resources commercially, knowledge about their fertilizer effect (N availability) is required to predict yield and impact on environment. The N fertilizer value of organic materials are dependent on highly unpredictable environmental factors, such as humidity, temperature and oxygen, and on the chemical quality of organic materials (e.g. C:N ratio) (Nicolardot et al. 2001; Jensen et al. 2005). In addition, synchronization of N mineralization with crops N demand will reduce the risk for N being lost from the soil as nitrate (NO_3^-) or as N gasses (N_2O, NO, NO_2 or N_2) from denitrification processes (Borgen et al. 2012; Hayakawa et al. 2009; Øvsthus et al. 2015, 2017). Recently, a study of pelleted compound recycling fertilizers aimed at a balanced nutrient ratio, by combining N- and phosphorus (P)-rich wastes with K-rich material (Brod et al. 2018). Results showed a good durability of the pellet product, but in this case a too low N-concentration relative to P and K according to the crop demands.

To our knowledge, there is no documentation in the published literature on the production of SS pellet fertilizers and its technical quality regarding practical use. Further, only one study in field conditions (Øvsthus et al. 2017) have focused on plant growth and NRE for SS used as fertilizer, and no studies have dealt with both N mineralization and potential denitrification (N_2O-emissions) for this product. Therefore, this study address a method for SS pellet production, demonstrate its N-effect on plant growth in various climates, and investigate potential N losses to the environment. We do this by means of the following objectives: 1) to document the possibility to produce a SS pellet fertilizer, including technical quality descriptions, 2) to record potato growth, N-uptake and NRE at three fixed temperatures in a pot experiment with SS pellet fertilizer, and 3) to assess N_2O emissions and N mineralization in an incubation experiment with both pellets and powder of SS.

Materials and Methods

Shrimp shell pellet production

Fertilizer materials, pellet production and -quality: The SS powder was based on dried SS and heads (*Pandalus borealis*) from Bioprawns AS, Nord-Lenangen, Norway. Experimental pellet samples were produced at Nofima, Bergen, Norway. A mix containing 940 g kg^{-1} of the SS powder, 50 g kg^{-1} whole-wheat flour (Norgesmøllene AS, Vaksdal, Norway) and 10 g kg^{-1} soy bean oil (purchased locally) was prepared and homogenized. The dry mix, calibrated to 150 kg h^{-1}, were processed in an atmospheric double differential preconditioner (Wenger Manufacturing Inc., Sabetha, KS, USA) followed by extrusion on a TX-52 co-rotating, fully intermeshing twin-screw extruder (Wenger). Nine circular 3.5 mm dies restricted the extruder outlet. The feed mixture was extruded with a total steam and water flow at 16.1 and 24.9 kg h^{-1}, respectively. The wet extrudates were cut at the extruder die surface to an approximate length of 4 mm and dried at 70 ºC in a hot air dual layer carousel dryer (Model 200.2, Paul Klöckner GMBH, Nistertal, Germany). A total of 227 kg pellet were produced, and 220 kg retained after sieving on a 2 mm screen (i.e. a process yield of 97%). The final sieved pellets were stored in closed containers at ambient temperature prior to analysis and shipment.

Initially, trial productions were performed on a pellet mill with 5 mm ring die holes (Simon Heesen, The Netherlands). However, neither process yield, nor physical pellet quality was considered as satisfying using the pellet mill in this experiment.

The following physical quality parameters of SS powder and pellets were studied: Pellet diameter was measured with an electronic calliper and based on averages of 20 pellets. Mechanical durability was measured by use of a tumbling box (Matador, Esbjerg, Denmark). A 500 g pellet sample was rotated 500 times in a rectangular box. After the test cycle, the amount of pellets remaining on a 2 mm screen was measured, and durability expressed as the weight-percentage of pellets retained. Durability are based on averages of duplicate analyses. Bulk density was measured by loosely pouring the SS powder or pellets through a funnel into a 1000 ml measuring cylinder. A dust fraction was defined for the SS powder as the percent passing through the 325 mesh sieve (<44 µm; air jet sieve Alpine A200LS-N, Hosokawa Micron Ltd., Cheshire, UK).

Pot experiment with potatoes

Experimental conditions and potato material: Experiments were carried from 25th of April to 27th of August 2008 at the phytotron of The Arctic University of Norway (UiT), located at Holt, Tromsø (69.7 °N, 18.9 °E). Conditions in the climate chambers were fixed temperatures (± 0.5 °C), natural daylight, and air humidity standardized at a water vapour pressure deficit of 0.5 kPa. The potato material was pre-basic seed tubers (about 30 g) of the medium early Norwegian cultivar Troll. Growing substrate was a 60:10:30 (v/v) mixture of 1) moist nutrient-deficient peat ("Naturtorv", natural sphagnum peat, Tjerbo Torvfabrikk AS, Rakkestad, Norway), with addition of 6 kg lime ($CaMg(CO_3)_2$, Franzefoss Bruk AS, Ballangen, Norway) per 1000 L usable volume, 2) sand (approx. 0.1-2 mm) and 3) perlite

(Agra perlite, Rhenen, Netherlands, 0-6.5 mm). The pH in the substrate after liming was expected to be 5.5-6.5, similar to standard fertilized peat from the producer. Pots, with drainage openings 5 cm above bottom, were filled with 10 L (7 kg) each of this substrate.

The extruded pellet product had a dry matter (DM) content of 90.2%, total organic carbon (TOC) content of 28.8%, C:N-ratio of 4, pH of 9.2, and a nutrient content of 7.2% N (Kjeldahl), 2.7% P, 0.1% K and 0.4% S of DM (Øvsthus et al. 2015). The ammonium and nitrate contents in the pellets were 0.3 and <0.1 g kg^{-1} DM, respectively. Due to limited content of potassium (K) and some micronutrients (eg. Mn) in SS, additional potassium sulfate (K_2SO_4, 41% K, Yara, K + S Group, Germany) and fritted trace elements (F.T.E. no. 36; Mn, B, Fe, Zn, Cu, Mo) were added separately into the growth medium. Mineral fertilizer (MF) was applied as NPK 11-5-18 (Yaramila Fullgjødsel®, Yara International, Norway).

Experimental design and treatments: The experiment was set up with five treatments; three levels of SS pellets, one level of MF and control (no fertilizer; NF) (Table 1). Total amounts of N supplied per 10 L pot (one plant) were 0.68, 1.35 and 2.03 g for treatment SS1, SS2 and SS3, respectively, and 1 g N for the MF treatment, equivalent to 100 kg available N ha^{-1} (Table 1). The N-levels for the SS treatments were aimed at an approximate equivalent to 50, 100 and 150 kg available N ha^{-1} in field application, and the N-availability for SS2 was assumed equal to MF. The calculations were based on previous experiences with potatoes in pot experiments, with an assumption of 80% N-availability for SS (Tor J. Johansen, unpublished results). Rates of the additional K and micronutrients were set at amounts corresponding to the K and Mn content in MF for SS2, ± 50% for the lower and higher SS levels, respectively.

Fertilizers were mixed into the growing substrate in the upper 1/3 level of each pot and seed tubers were planted at 5 cm depth. Experiments were performed at three growth temperatures (9, 15 and 21 ºC) with six pots for each of the five treatments at each temperature. Pots were placed on trolleys (two pots on each), and were randomly positioned within the chambers at weekly intervals. Water was supplied daily at demand (estimated), and once a week up to a defined pot weight for each treatment (7 kg + weight of the increasing plant biomass).

Growth data and chemical analyses: After planting, the time for emergence of sprouts was recorded for individual plants. Further observations were done at harvest (68, 82 and 124 days after planting, for plants grown at 21, 15 and 9 ºC, respectively). The timing aimed at approximately similar developmental stages of the MF treatments at these growth temperatures. At harvest, the following data were recorded: percent fresh (green) haulm by subjective visual estimation, number of aboveground stems, total number of tubers (included stolon tip swellings above 10 mm), fresh matter (FM) and dry matter (DM) of total biomass (separated in haulm (aboveground stems and leaves), underground stems and roots, and tubers). Finally, FM biomass and percent DM content (based on specific gravity) of tubers were recorded. For the chemical analyses of total N content (TN) in plants (tubers, haulm, roots, underground stems and roots) after harvest, samples were combined for two and two pots (three samples per treatment). Eurofins Food and Agro Testing Norway AS performed the analyses.

N-recovery efficiency: N-recovery efficiency (NRE) is an expression of the rate N applied taken up by the plant, after subtraction for uptake from unfertilized plants (NF). Calculations were performed according to the following formula (Craswell and Godwin 1984): NRE = $(U-U_0)/N_A$, where U and U_0 are uptake of total N per plant grown with and without fertilizer, respectively. N_A is the amount of applied N per plant.

Incubation experiment

SS pellets and powder, respectively, at amounts equal to 110 mg N (corresponding to 300 kg N ha^{-1}) were incorporated in 100 g DM soil in 0.2 L open glass jars. The soil was a sandy, orthic humo-ferric podzol with pH 6.1, sampled at Vågønes, Bodø (a previous NIBIO research station). It contained 91% sand, and contents of total carbon and total N in the soil were 21 g kg^{-1} and 1.7 g kg^{-1}, respectively. The samples were incubated at 15 °C at constant humidity (25 g water in 100 g DM soil) for 100 days in an incubation chamber (Termaks B8420S, Norway, Bergen). Soil without SS material was incubated as control. The water level was maintained by regulating the weight up to 125 g twice a week. The field capacity of the soil was 30% but we chose to keep the humidity slightly lower to avoid anaerobic conditions, corresponding to 67% of field capacity. During the incubation experiment, the glass jars were covered by a plexi-glass with drilled holes to ensure constant humidity.

Total sample number for incubation at the start of the experiment (day zero), were 15 for each of the SS materials (powder and pellets). In addition, 3 samples (not incubated, control) with each material were stored directly at -18 °C in plastic zipper bags. At increasing intervals at day 1, 14, 21, 69 and 100, three samples were taken out of the incubation chamber and stored similarly as above at -18 °C. All these samples were analysed for mineral N according to NS-EN ISO 11885, after extracting 40 g frozen soil samples in 200 mL of 1 M KCl prior to analyses. During the incubation period, at day 0, 5, 15, 35, 72 and 100, the incubated glass jars were sealed for one hour by using a lid. Gas samples from all the remaining incubated glass jars each time (decreasing numbers) were taken by using vials crimp seal serum glass and a needle for gas samples through a silicone stopper in the lid. Gas samples were analysed by gas chromatography.

Statistics

The pot experiment had a complete 5 × 3 factorial design (five fertilizers incl. control, three temperatures). The data were analyzed using two-way analysis (fertilizers, temperatures) followed by a one-way analysis for each temperature (ANOVA, GLM procedure). Analyses were performed by Minitab 16.1.0 (Microsoft, State College, PA, USA). Tukey multiple comparisons test were used for pairwise comparisons of treatments, with a setting of $\alpha = 0.05$.

In the incubation experiment, there were three samples (replicates) for each sampling date for mineral analyses, and a decreasing number of replicates (remaining samples) for each gas sampling date. The values from the measurements of mineral N and nitrous oxide emissions fluxes are presented as averages and standard deviations.

Results and Discussion

Experimental SS pellet production

Based on initial testing it was not possible to extrude the SS powder without the addition of a lubricator and binder. The low fat content created a high friction and heat, resulting in blocked extruder die holes. In addition, the low powder binding properties (low protein, high ash) gave poor pellet durability. The same results were also achieved during initial testing on a pellet mill. Wheat is considered as a first-choice starch-based binder in feed pellets (Thomas and Van der Poel 1996; Ytrestøyl et al. 2015) and as a first approach, selected in this study.

Soybean oil was selected as the lubricator. Both ingredients are easily accessible. The pellet had a diameter of 3.6 ± 0.1 mm, which is within the expected range for a fertilizer pellet.

The mechanical durability test simulates the forces applied during transportation and distribution (Thomas and Van der Poel 1996). The pellet product had a durability of 94%. This may allow successful mechanical spreading in field, although not tested in this study. The SS powder had a high dust fraction (18% <44 μm) and low bulk density (317 g L^{-1}) and was therefore of limited relevance due to storage, transport and application challenges (generated a large amount of dust). The pellet product had a density of 467 g L^{-1}. This is lower than commercial organic and mineral fertilizers which have bulk densities in the range of about 650 – 1000 g L^{-1}. However, the high durability and a highly reduced dust problem made it more suitable for use as a fertilizer compared to the SS powder. The aim for the project was to document the possibility to produce a SS pellet fertilizer and economical optimization was not the scope of this study. Extrusion processing is more costly than pelletizing, and due to the downstream drying step, a wet process are costlier than a dry process. Nevertheless, suggested further work is to optimize the pellet production process for reduced processing costs and optimize the level and type of binder used. This can be other starches, molasses, lignosulfonates, clay, bone meal or fish silage. It is also important to further study the effect of processing and pellet physical properties on the dissolution rate and N-availability. Finally, a pellet product with a balanced nutrient ratio, by adding of K-rich resources, would make it more relevant for practical use (Brod et al. 2018).

Potato growth

The results clearly showed that SS is an effective potato fertilizer, thus with slightly lower tuber biomass than for MF at similar plant-available N-levels (Table 2). However, results showed a tendency of later plant emergence, fewer stems, later haulm growth cessation, and lower tuber numbers for the SS fertilizer than for MF. The delayed emergence and growth cessation are probably caused by a delayed N-availability from the organic SS fertilizer compared to MF. These growth chamber results are in accordance with results from previous field trials (Tor J. Johansen, unpublished).

Stem numbers did not seem to vary with levels of SS. However, there was a tendency of increasing tuber numbers per stem with increasing levels of SS fertilizer. This is difficult to explain, but is probably influenced by higher N- or P-availability (see Table 1) at higher fertilizer levels (Jenkins and Ali 2000). In general, tuber numbers and sizes are regulated by complex interacting mechanisms, and are determined by numbers of stems per plant, number of tubers per stem, and yield (Struik et al. 1990).

N uptake, N recovery efficiency and N availability

For all growth temperatures, the total N uptake at the various fertilizer treatments was highest for SS3, lowest for SS1 and intermediate for SS2 and MF, thereby following the ranking of applied N (Table 3). Interestingly, the total N uptake for MF and SS2 at all temperatures were approximately at the same levels, indicating similar N availability of the supplied 1 g MF and 1.38 g SS per pot.

NRE in this potato trial was around 90% for MF, and about 70% for the different levels of SS (Table 3). The high NRE for MF indicate a low level of N lost as gases (nitrous oxide, nitrogen dioxide, nitric oxide or ammonia), and a high level of N utilization in the produce. Under field conditions, there is a potential risk for leakage as the N supplied as MF is available for the plants at application. However, in this experiment, leakage from pots is not relevant, and only N lost as gas (denitrification or ammonia volatilization) or N bound in structural chemical compounds, may cause unavailability.

NRE is dependent on the N fertilization amount, and are in general highest when the fertilization rate is low. Thus, as the NRE is equal for all SS pellet treatments, it indicates that the potato can use the entire available N from all three supplied amounts of SS pellets (approximately 70%, Table 3). The NRE after all SS fertilization treatments was low compared to MF, which show that about 30% of added N is unavailable and bound in highly complex chemical structures, or lost as gases. The results matched N mineralization for SS powder in the incubation experiment, but not for SS pellets (67% and 39%, respectively, Fig. 1), which indicate better conditions for N mineralization in the pot experiment than in the incubation experiment. These deviating results might be explained by different soil texture and moisture conditions, in accordance with studies by Jones et al. (2007) and Hayakawa et al. (2009).

SS powder has approximately the same chemical property as SS pellets, and the humidity, pH and temperature during incubation were equal for the two materials. The physical property is thereby the main difference between powder and pellets, and the main explaining factor for differences in mineral N amount after incubation. In the mineralization process, the compact concentration of organic material in the pellets, might lead to higher microbial activity around and inside the pellets (anoxic hotspots), which favour denitrification instead of nitrification in the N cycle (Breland 1994; Cabrera et al. 1994a, b; Petersen et al. 1996). This theory corresponds well with the denitrification fluxes for SS pellets and SS powder in our studies (Figure 2). Additional factors is that powder has a higher probability for dissolving, and a greater surface for microbial attack than pellets.

In conclusion, it is possible to produce a SS pellet product that can be used as a potato fertilizer (with potassium supplements), thus with a delayed N-availability compared to mineral fertilizers. The NRE of SS pellets was on average around 70% in the pot experiment, showing that about one third of the added N as SS pellets might be unavailable for the potato plants during the growing season. The risk of N-loss trough N_2O emissions, demonstrate a need for further knowledge of potential denitrification for SS pellets under field conditions. For practical relevance of the product, a more balanced nutrient ratio by adding K-rich material to the pellets would be advantageous.

Disclosure

The authors declare no competing financial interest.

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Table 1 Applied fertilizers and supplemental nutrients, and total NPK contents per 10 L pot (one potato plant). Treatments were mineral fertilizer (MF), pellets of shrimp shell powder in increasing fertilizer rates (SS1-3) and no fertilizer (control, NF). Potassium (K) was applied as K_2SO_4 and micronutrients as F.T.E. no. 36

Applied fertilizer and nutrients per pot				Total NPK contents		
	Fertilizer	K_2SO_4	FTE 36	N	P	K
Fertilizer	(g)	(g)	(g)	(g)	(g)	(g)
MF	9.1	0.00	0.00	1.00	0.42	1.62
SS1	10.4	1.95	0.68	0.68	0.31	0.81
SS2	20.8	3.90	1.36	1.35	0.62	1.62
SS3	31.2	5.85	2.04	2.03	0.93	2.43
NF	0.0	0.00	0.00	0.00	0.00	0.00

Table 2 Average potato (*Solanum tuberosum*) growth data (n=6) at emergence and harvest from a controlled climate trial with various fertilizers (F) and dosages at three temperatures (T). Pellets from shrimp shell powder in three N-levels (SS1-3; estimated plant-available N-dosages of 50, 100 and 150% of mineral fertilizer, MF) and no fertilizer (control, NF)

Temperatures and fertilizers	Emer-gence (days)	No. of stems per plant	Haulm maturity (% green-ness)	Haulm DM (g per plant)	No. of tubers per plant	Tuber FM (g per plant)	Tuber DM[a] (%)
9 ºC (124 d)							
MF	19.5b	7.3a	10.8c	11.0b	30.8a	413a	23.2bc
SS1	24.2a	4.7b	40.8ab	6.1c	11.0bc	237b	23.9ab
SS2	23.3a	3.8b	46.7ab	10.5b	15.5b	363a	22.6bc
SS3	23.2a	4.8b	63.3ab	13.3a	14.3b	407a	21.7c
NF	24.5a	3.2b	20.0bc	0.8d	4.5c	51c	25.2a
15 ºC (82 d)							
MF	11.7	6.5a	21.7c	15.7b	14.3a	390a	23.5ab
SS1	12.5	4.2b	27.5bc	8.5c	8.7b	216c	24.6ab
SS2	13.7	4.0b	44.2b	16.4b	11.0ab	268b	23.7ab
SS3	13.3	3.8b	64.7a	28.0a	10.5ab	314b	22.2b
NF	15.3	2.8b	15.0c	1.2d	2.0c	59d	26.2a
21 ºC (68 d)							
MF	8.8b	5.8	9.2b	18.5b	18.2a	364a	22.2a
SS1	10.0a	5.5	19.2b	10.9c	7.5c	192c	22.7a
SS2	10.0a	4.2	26.7b	19.3b	13.3b	294b	22.3a
SS3	10.0a	4.7	60.0a	28.1a	17.5ab	294b	22.9a
NF	10.5a	3.2	10.0b	2.1d	2.5d	36d	23.6a
P-values (ANOVA)							
T	0.000	0.505	0.003	0.000	0.000	0.000	0.003
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000
T×F	0.172	0.851	0.398	0.000	0.000	0.002	0.111

Growth periods (d) were different at the various growth temperatures

Values within columns not having any lowercase letters in common are significantly different by Tukey's multiple comparisons test

[a] Tuber dry matter (DM) measurements are based on merged tubers from two and two plants at each temperature (n=3)

Table 3 N-application, N-uptake and N recovery efficiency (NRE) per plant in potato (*Solanum tuberosum*) for mineral fertilizer (MF) and three levels of shrimp shell (SS1-3). NF is control with no fertilizer. Average results (n=3), ± SEM for NRE

Temperatures and fertilizers	N-applied (g)	N-uptake Haulm (g)	N-uptake Tubers (g)	Total N-uptake (g)	NRE
9 °C (124 d)					
MF	1.00	0.20c	0.73b	0.94b	0.83 ±0.04
SS1	0.68	0.15c	0.48c	0.63c	0.77 ±0.05
SS2	1.35	0.27b	0.74b	1.02b	0.67 ±0.06
SS3	2.03	0.38a	1.03a	1.43a	0.65 ±0.03
NF	0.00	0.01d	0.09d	0.11d	
15 °C (82 d)					
MF	1.00	0.33c	0.68ab	1.03b	0.93 ±0.02
SS1	0.68	0.18d	0.36c	0.55c	0.66 ±0.03
SS2	1.35	0.49b	0.58b	1.08b	0.73±0.02
SS3	2.03	0.76a	0.76a	1.53a	0.70 ±0.04
NF	0.00	0.02e	0.08d	0.10d	
21 °C (68 d)					
MF	1.00	0.29bc	0.75a	1.07b	0.94 ±0.02
SS1	0.68	0.21cd	0.39b	0.61c	0.71 ±0.09
SS2	1.35	0.42b	0.61a	1.06b	0.69 ±0.02
SS3	2.03	0.82a	0.71a	1.56a	0.71 ±0.02
NF	0.00	0.03d	0.08c	0.12d	
P-values (ANOVA)					
F		0.000	0.000	0.000	
T		0.000	0.000	0.145	
FxT		0.000	0.002	0.386	

Growth periods (d) were different at the various growth temperatures

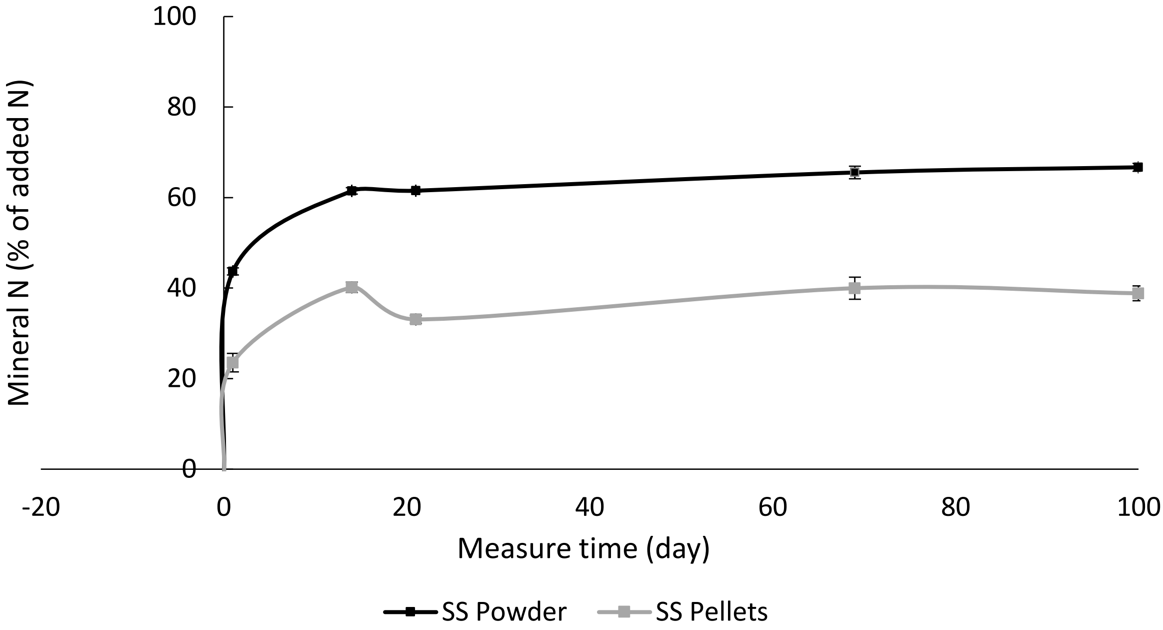
For each temperature, values for N application and uptake within columns not having any lowercase letters in common are significantly different by Tukey's multiple comparisons test

Figure captions:

Fig. 1 Mineral N (NO_3^- and NH_4^+) mineralized from shrimp shell (SS) pellets and SS powder during 100 days of incubation in soil at 15°C and constant humidity. Average results (n=3) ± SD

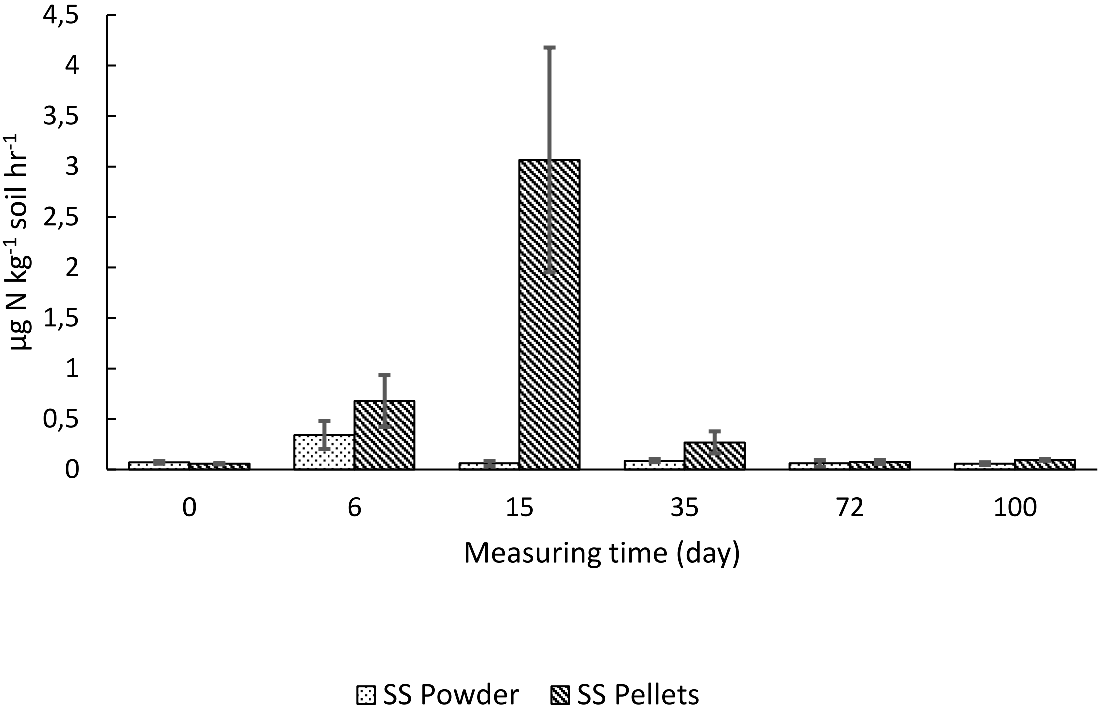
Fig. 2 Nitrous oxide (N_2O) emissions from shrimp shell (SS) pellets and SS powder during 100 days of incubation in soil at 15°C and constant humidity. Average results (n varying) ± SD

Fig. 1



100
80
60
40
20
0
-20
0
20
40
60
80
100
Mineral N (% of added N)
Measure time (day)
SS Powder
SS Pellets

Fig. 2



4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
μg N kg-1 soil hr-1
0
6
15
35
72
100
Measuring time (day)
SS Powder
SS Pellets