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Invasive Plants in Support of Urban Farming: Fermentation-Based Organic Fertilizer from Japanese Knotweed

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Abstract: In this study, fermentation-based organic fertilizer (OF) was produced from the above-ground parts of *Fallopia japonica* (Houtt.) Ronse Decr. The quantity of N in OF (17.2 kg t^{-1} fresh lactic-fermented OF) was higher than average in cattle farmyard manure, but on a comparable level to solid poultry and rabbit manure. The OF was applied on a field to evaluate its effect on Chinese cabbage. The applied nutrients with OF N159 were 159, 19 and 100 kg ha^{-1} for N, P, and K, respectively. The applied nutrients with OF N317 were 317, 38, and 200 kg ha^{-1} for N, P, and K, respectively. The average mass of marketable Chinese cabbage (*Brassica pekinensis* Rupr.) single heads ranged from 253 g with N0 treatment to 602 g with N317 treatment. The nutrient recovery efficiency $RE_{N,P,K}$ was 37, 20, and 50% for N317 and 55, 48, and 77% for N159. The OF was found to be a suitable alternative to farmyard manure. Additionally, OF produced from *F. japonica* could complement existing approaches to limit the spread of invasive species in cities. Further research should focus on perennial crop rotations and cropping patterns, different soil types, and a greater variety of crops and consider the possible retention of urban farmers using fertilizer from invasive plants.

Keywords: Japanese knotweed; Fallopia japonica; fermentation; organic fertilizer; urban food production; land management

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1. Introduction

Fallopia Japonica (F. Japonica) is a fast-spreading invasive herbaceous plant mainly known for its ecosystem disservices. *F. japonica* causes considerable economic and environmental damage throughout the USA, UK, and Europe [1,2]. Due to its ability to quickly spread, it reduces the diversity [3–5] and the activity [6] of native biota, increases soil erodibility [7], affects temporal patterns of soil nutrient availability [8], and causes significant structural and functional changes in urban and rural ecosystems [9]. As such *F. japonica* poses considerable economical, planning, and logistical problem in urban and rural land management [10].

To control its spread, different mechanical, chemical, and biological approaches have been applied individually or in combination. Control methods that integrate a variety of options can lead to near-effective control of *F. japonica* [11]. Mechanical control methods, such as hand cutting, mowing, grazing, digging, pulling, and covering have proven labor-intensive but in some cases still lackluster in limiting *F. japonica*'s growth. The spread of *F. japonica* is to some extent controllable with herbicides [12], and biological agents, such as psyllid *Aphalara itadori Shinji* [13] and the fungus *Mycosphaerella polygoni-cuspidati* [14]. The restoration of contaminated areas requires careful species selection due to the allelopathic effects of *F. japonica* [15]. For example, fast-growing *Salix viminalis* significantly reduces knotweed spread due to its rapid growth and, therefore, represents promising restoration of species in some urban environments and riparian zones [16].

F. japonica is also known for its numerous ecosystem services. The aerial or underground parts of *F. japonica* show insecticidal [17] and fungicidal potential [18], and have been successfully used in the production of medicine [19], biofuel [20], briquettes for heating [21], paper cellulose fibers [22], textile [23], and as carbon (C) adsorbent [24]. In some of these production processes, the aerial parts of the plant went unused and were disposed of in landfills, although these parts weigh more than half the total mass of the plants [12,19]. To avoid resource waste and develop new potential benefits, it was suggested to focus research and development on the added value of the aerial parts [19]. Existing research has not yet focused on the potential uses of the aerial parts on *F. japonica* in the production of organic fertilizer (OF), although the high nitrogen (N) sequestering and remobilization ability of *F. japonica* [1] indicates that such uses might be possible, and attempts in composting *F. japonica* for the production of OF have proven promising [25].

We tested the aerial parts (leaves and stems) of *F. japonica* as raw material for the production of OF and applied the fertilizer on a field to evaluate *F. japonica*'s effects on Chinese cabbage and agricultural soil. OF was, for the first time, produced by a fermentation process using a microbial inoculant known as effective microorganisms (EM). It is reported that fermented OF possesses advantages over composts, including easier and more environmentally friendly preparation from the raw material [26]. The use of fermented products rich in selected microorganisms has positive effects on soil biological activity and may improve physical and chemical soil properties, and plant growth [27–29].

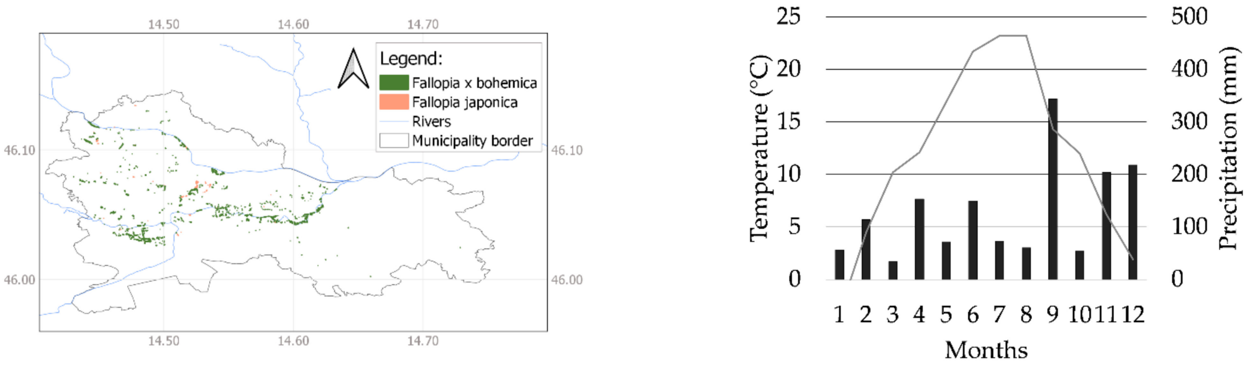
We hypothesized that the OF produced from *F. japonica* would successfully replace farmyard manure, which is not easily obtainable or handled in an urban environment. Furthermore, we assumed that mineralization and nutrient availability would be faster than those from other, comparable composts. This approach could serve as an alternative method for managing the uncontrolled spread of *F. japonica* in urban areas.

2. Materials and Methods

The presented experiment focuses on the management problem of *F. japonica* in the case-study city of Ljubljana (Slovenia), where approximately 5 ha of municipality-owned land is infected by *F. japonica* stands, and a further 30 ha is infested by *F.* × *bohemica* [30,31] (at least 0.13% of the total municipal area) (Figure 1a). The experiment was conducted in August, September, and October 2017. The average monthly air temperature in 2017 was 11.9 °C, and the annual precipitation was 1531 mm. The monthly average temperatures were about 1 °C above, 1 °C below, and within the long-term average (1981–2010) during all three months. The monthly precipitation in August and October was half the long-term average. September was extremely wet, with twice the amount of the long-term average precipitation. The daily maximum temperatures in months 8, 9, and 10 were 30.2 °C, 19.1 °C, and 18.7 °C, respectively. The minimum daily temperatures in months 8, 9, and 10 were 16.7 °C, 11 °C, and 6.7 °C, respectively [32]. Although the heatwave shortly after planting in early August slowed down the initial growth of the plants, the conditions in September and October were favorable for the growth of Chinese cabbage (Figure 1b).

The aerial parts of *F. japonica* were harvested from infested grassland near a recreational pathway (46°02′48.36″ N, 14°33′51.80″ E) on 19th May 2017. Each shoot was cut approximately 5 cm above the ground to avoid harvesting roots with high vegetative reproduction potential. The plant material was collected from an unmanaged patch (29% of the harvested area) and from a one-month-old patch (71% of the harvested area). In total, 100 kg of fresh plant material was collected from a total area of 42 m^2.

The plant material was stored in jute bags and transported to the facilities of the Biotechnical Faculty of the University of Ljubljana, where it was air dried at 40 °C for two days and then cut by machine in to pieces 1–5 cm long. The chopped plant material was transferred into two plastic 73- and 62-L barrels with screw caps, which were filled up to 57 L (i.e., three-quarters of a barrel) and 31 L (half a barrel), respectively. The plant material was layered into the barrel in approximately 2 cm thick horizons. One fistful (30 g) of EM Bokashi—a commercial product made of lactic acid bacteria, yeast, and photosynthetic bacteria grown on a substrate of cereal bran and molasses—was spread on each horizon (30 g per 5.6 L or ca. 850 g of freshly chopped *F. japonica* = 35 g/kg). The mass was then firmly pressed, expelling air from the pores.



(**a**) (**b**)

Figure 1. The (**a**) stands of *F. japonica* and *F.* × *bohemica*, and (**b**) average monthly air temperature (°C) (line) and precipitation (mm) (bars) in 2017 in Ljubljana (Slovenia).

The plant material was covered with plastic foil, weighted with bricks and plastic bags filled with water, and closed with the screw caps to ensure no air entered the barrels during the process. The material was left to ferment in a dark and unheated room for two months. The average air temperature during fermentation was around 20 °C during the day and 10 °C during the night. The input plant material before fermentation and the output OF after fermentation were analyzed according to the Weender analysis—a partitioning and quantification of moisture (103 °C, 4 h), crude ash (ISO 5984:2002), crude protein (ISO 59832:2009) (or Kjeldahl protein), crude oils and fats (EC 152/2009, annex II H Procedure A), crude fiber (ISO 6865:2000), and N-free extracts (digestible carbohydrates). The fermented *F. japonica* to be further used in the experiment as OF was analyzed for organic fatty acids (water extraction, followed by esterification and analysis with GC-FID) (Tables 1 and 2). A composite (bulk) sample of 15 individual samples (increments) was collected for both analyses (ISO 18400-102:2018).

The fertilization experiment was carried out in the multipurpose public urban green area, LivadaLAB (46°01′47.95″ N, 14°30′37.54″ E). The soil of the experimental field was a typical mineralized organic soil over a former lake and river sediment of lime gyttja and clay, and the texture was silt-loam. The characteristics of the plough horizon (0–20 cm) were as follows: pH ($CaCl_2$) 6.5, plant available phosphorus (P_2O_5) 45 mg kg^{-1} dry soil (ammonium lactate method; A level according to the Slovene guidelines for professional fertilization [33]), and plant available potassium (K_2O) 122 mg kg^{-1} soil (ammonium lactate method; B level [33]). The soil contained 12.55% of organic matter, 7.25% C, 0.64% N, and a C-to-N ratio of 11:5. In the last 10 years, the soil at the site was not utilized for agricultural production, not fertilized, and used as grassland, and the vegetation was cut once a year to prevent overgrowing with bushes and trees. The cut grass was removed from the site.

The soil was prepared by plowing with a moldboard plow 25 cm deep. Next, we crumbled the furrows and prepared the soil by harrowing, leveling, and forming raised beds. The soil was then saturated with water up to approximately 80% of the field's capacity, which was suitable for transplanting the seedlings of Chinese cabbage.

Table 1. Nutrient content of fermented F. japonica (OF) (% in fresh matter) and major nutrients application.

Major Characteristic	N	P	K
% DM in OF = 49.6			
Nutrients content in OF (% fresh matter)	1.59	0.19	1.00
Applied nutrients with OF N159 (kg ha^{-1})	159	19	100
Applied nutrients with OF N317 (kg ha^{-1})	317	38	200

Table 2. Properties of organic fertilizer (OF) made of *F. japonica* and Bokashi compost starter mixture before and after lactic fermentation.

Properties	*F. japonica* before the Start of Fermentation		Lactic-Fermented OF	
Fraction	Sample	Dry matter	Sample	Dry matter
Dry matter (g/kg)	374	1000	496	1000
Moisture (g/kg)	626	/	504	/
Crude protein (f = 6.25) (g/kg)	76	203	91	184
Crude fibers (g/kg)	90	240	39	79
Crude ash (g/kg)	38	101	118	237
Crude fat (g/kg)	6	16	9	18
pH	4.5	/	4.60	/
Lactic acid (g/kg)	/	/	6.60	13.3
Acetic acid (g/kg)	/	/	3.47	7.00
Propionic acid (g/kg)	/	/	0.05	0.09
Butyric acid (g/kg)	/	/	0.16	0.32
Valeric acid (g/kg)	/	/	0	0
C (%)	/	/	23.2	46.8
N (%)	/	/	1.59	3.21
C/N	/	/	.	14.5
NO_3-N (mg/kg)	/	/	<1	<1
NH_4-N (mg/kg)	/	/	12.4	25.0
P (%)	/	/	0.19	0.39
K (%)	/	/	1.00	2.01

The planting date was August 6, 2017, and the harvest date was 17 October 2017. The seedlings with four true leaves (approx. 8 cm in height) of Chinese cabbage were transplanted into the soil at a density of 14 Yuki F1 plants per 1 m^2 at a distance of 30 cm in each row, with 20 cm between rows. The crop was treated with OF at a rate of 0, 1, and 2 kg m^{-2}; the total amount of N applied in each treatment was 0 kg N ha^{-1} (treatment N0), 159 kg N ha^{-1} (treatment N159; small dose; 10 t ha^{-1}), and 317 kg N ha^{-1} (treatment N317, large dose; 20 t ha^{-1}) (Table 1). The OF was incorporated in soil (5 cm deep) manually just before planting.

The total area of the experimental site was 22.14 m^2 (5.4. m × 4.1 m), organized as three slightly raised beds (ca. 10 cm high). Three experimental blocks were prepared, and one replicate of each treatment was randomly assigned in each block. Protection bands 0.5 m wide were formed between experimental blocks and bands 0.3 m wide were formed between experimental plots within each block to prevent the influence of fertilizers from the neighboring sectors. Each plot had an area of 1 m^2 (1.4 m × 0.7 m).

Nearly all of the N in the OF was organically bound. Only traces were found in the form of ammonium, which is surprising, as anaerobic digestion usually leads to a greater amount of ammonia [34,35]. Nitrate and nitrite forms were measured but not detected (Table 2). The chosen fertilization rates fell both below and above the common practice of vegetable growers, who use a fertilization target value of 240 kg ha^{-1} mineral N to achieve 50 t ha^{-1} of fresh Chinese cabbage yield [33]. Since all the N was organically bound in the OF, we expected that only a small percentage would be released over the two months of our Chinese cabbage growth experiment.

Pesticides were not used in the experiment. The plants were irrigated according to visual observations every second day in August using an irrigation bucket. Then, the plants were irrigated every fourth day. We irrigated approximately 10 mm of water per irrigation to the point that the first layer of soil (up to 4 cm) was determined to be wet with a finger test.

The yield of standard and non-standard heads and the total masses of plants were then measured by weighing. Five random plants from each plot were selected; one quarter from each plant was taken for further analysis (ISO 24153:2009). Plant samples were air-dried in a fan-aerated chamber at 40 °C to a constant weight and milled with a Retsch Cutting Mill SM 100 to a final fineness smaller than 1.0 mm. The air-dried and milled bulk samples were further analyzed for their total dry matter (SIST EN 13040:2008). The analyses for total C and N were performed with a Vario MAX instrument (Elementar Analysensysteme GmbH). This instrument operates on the principle of dry combustion, by simultaneously analyzing the C and N content and capturing organic and inorganic forms (SIST ISO 10694; SIST ISO 13878).

Ammonium and nitrate content were extracted with 0.01 M $CaCl_2$ through 2 h of shaking. Then, we filtered the extract through a 0.45 µm filter and measured ammonium and nitrate using a Thermo Scientific ™ Gallery ™ Plus Automated Photometric Analyzer (SIST ISO 14255:1999). For the elemental analyses of total P and K content, the samples were digested with multiple acids, which dissolved most of the minerals; 0.25 g of each sample was heated first in HNO_3, then in $HClO_4$, and lastly in HF until evaporation. Each sample was then dried, the residue was dissolved in HCl, and the elements were measured using an ICP-ES Inductively Coupled Plasma Emission Spectrometer [36].

Program R was used for statistical analyses, and the differences between treatments were estimated with the least significant difference test. The significance level was set at $\alpha = 0.05$.

Finally, the potential impact on urban food production was estimated based on the average yield of the fresh mass of *F. japonica* from the vegetation canopy in July (90 t ha^{-1}) [37]. We modeled the required application of fertilizer from *F. japonica* needed to cover the plant nutrient requirements of the selected vegetable crops at a given expected yield. The selection of crops was based on the research of Glavan et al. [38], who provided a detailed list of the 14 most commonly grown crops by urban allotment farmers in Ljubljana. This list represents the average allotment for a garden in Ljubljana. The calculation is based on the expected yield (t ha^{-1}) and expected crop nutrient uptake (kg ha^{-1}) given in the technological instructions for integrated vegetable production—plant production based on integrated plant nutrient and pest management [39].

3. Results

3.1. Organic Fertilizer Properties

The 100 kg of fresh *F. japonica* plant biomass harvested in May from 42 m^2 equaled a fresh-matter OF substrate per ha of 23.8 t ha^{-1}. After air drying, the 100 kg fresh matter OF substrate gave 0.088 m^3 of OF, equivalent of an OF quantity of 27.1 m^3 ha^{-1} or 0.88 t m^{-3}.

The properties of the OF made from *F. japonica* and EM Bokashi before and after lactic fermentation are shown in Table 2. During the 2 months of lactic fermentation, some water was lost from the mass of OF via cell lysis and metabolic water leaching out of the cells. The produced OF contained ca. 50% moisture. Although the OF retained most of its green color (Figure 2), it smelled similar to sauerkraut. The OF contained 9% proteins, 4% carbohydrates (mostly in form of fibers), slightly less than 1% fats or oils, and a relatively large fraction of 12% non-volatile (ash) material.

The OF was already acidic at the start of the experiment due to the addition of an acidic Bokashi compost starter. The fermentation process did not alter the acidity, which was at around pH 4.5. Lactic acid (6.6 g/kg) and acetic acid (3.5 g/kg) were prevailing organic acids in OF.

The quantity of N in fresh lactic-fermented OF was 15.9 kg t^{-1}. The ratio of C/N was 14.5:1. In OF, practically all N was in an organic form, less than 0.1% of N was in an ammonium form, and none was in a nitrate or nitrite form. The contents of P and K were 1.9 kg P t^{-1}, with 10.0 kg K t^{-1} of fresh OF. The ratio in kg t^{-1} of fresh OF was N:P:K = 16:2:10.

Figure 2. Fermentation-based organic fertilizer from the aboveground parts of *F. japonica*.

3.2. Soil Properties

After the harvest of Chinese cabbage, the soil analysis showed a significant improvement in soil-available P and especially K-levels (Table 3).

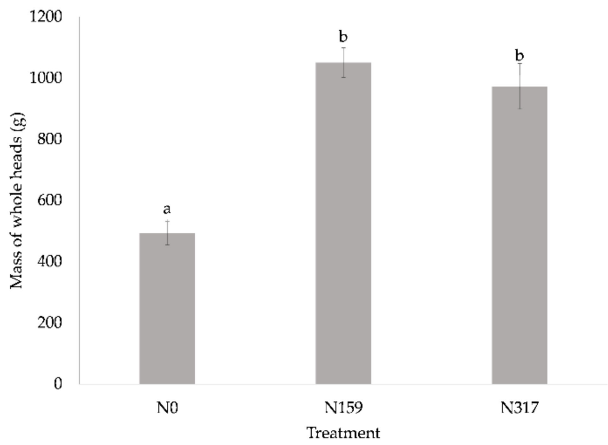
Table 3. Soil properties before fertilization and after the Chinese cabbage harvest.

Parameter	Before Fertilization	After Harvest		
		N0	N159	N317
pH ($CaCl_2$)	6.5	6.7	6.8	6.6
AL-P_2O_5 (mg/100 g)	4.5	4.1	5.7	6.2
AL-K_2O (mg/100 g)	12.2	19.0	24.7	27.5
NO_3-N (mg/100 g)	/	3.16	3.27	3.42
NH_4-N (mg/100 g)	/	0.36	0.28	0.31

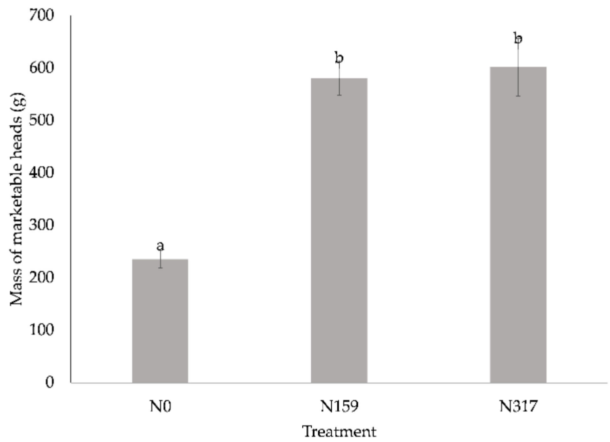
As aerial losses occur, fermented OF, in comparison to composted OF with the same origin, would probably contain a higher percentage of N. The addition of OF did not significantly change the soil pH or the soil mineral N content after the harvest despite the high application of total N in the treatment N317 (317 kg N ha^{-1}).

3.3. Plant Yield and Quality, Nutrient Uptake

The heads at N0 treatment were loose (unsalable heads). Despite this fact, we considered marketable all the parts of the heads that were edible. The mass of the whole heads was 40–50% higher than the mass of marketable heads. The mass of the whole heads (fresh) of Chinese cabbage ranged from 49.2 t ha^{-1} at treatment N0 to 100.5 t ha^{-1} at treatment N159 (Figure 3a). The average mass of marketable single heads in our experiment ranged from 253 g with N0 to 602 g with N317. The heads of OF treatments were significantly heavier than the heads in the control, but the average weight of N159 was not significantly different from that of N317 (Figure 3b). The diameter of marketable heads of Chinese cabbage ranged from 31.3 cm at treatment N0 to 39.7 cm at treatment N159 (Figure 3c).



(**a**)



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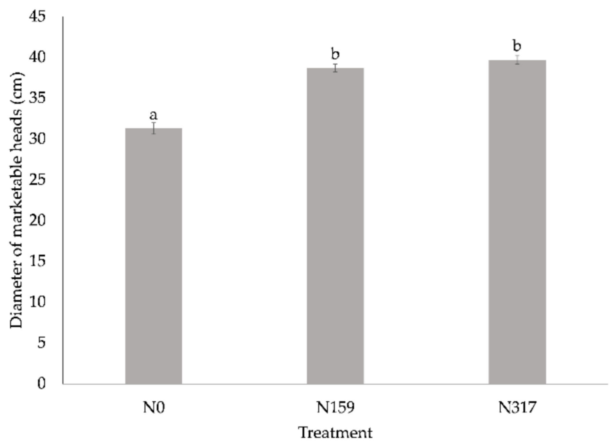

(**c**)

Figure 3. The (**a**) mass of whole heads (g), (**b**) mass of marketable heads (g), and (**c**) diameter of marketable heads (cm) (mean ± SE); a and b lower case letters denote statistical significant differences ($\alpha < 0.05$) among treatments.

The ANOVA analysis showed that there were no statistically significant differences between fertilization treatments (independent variable) in the average contents of C, N, NO_3-N, P, and K (dependent variables) in Chinese cabbage plants. The K (%) achieved in our research ranged between 2.1 and 2.6% (Table 4).

Table 4. Average contents of C, N, NO_3-N, P and K in the crop of air-dried Chinese cabbage plants.

Treatment	C (%)	N (%)	C/N	NO_3-N (mg/kg)	P (%)	K (%)
N0	40.6	4.6	8.8	2678	0.4	2.1
N159	39.6	4.2	9.4	3054	0.4	2.7
N317	40	3.9	10.3	2598	0.3	2.6

Dry matter content was 9–11%, and did not statistically differ between the fertilizations (Table 5). The difference in yield between the fertilization levels of N0, N159, and N317 decreased with increasing fertilization intensity (Tables 4 and 5).

Table 5. Dry matter content (DM) (%) and yield (kg DM ha^{-1}) of Chinese cabbage plants.

	N0	N159	N317
DM content (%)	11	9	11
Yield (kg DM ha^{-1})	2320	4632	5734

The uptake of the major nutrients N, P, and K by plant biomass is listed in Table 6. In brackets, the apparent uptake from the OF used in the experiment is also provided, calculated as the difference between the N uptake at N0 variant and the N159 and N317 fertilization treatments.

Table 6. Nutrient uptake by the yield of Chinese cabbage and apparent uptake from OF (in brackets) in kg/ha.

Nutrient Uptake by the Crop and Apparent Uptake from OF (kg/ha)			
Treatment	**N**	**P**	**K**
N0	107	9	49
N159	195 (88)	18 (9)	125 (76)
N317	224 (117)	17 (8)	149 (100)

The relationship of nutrient plant uptake from OF by Chinese cabbage (Table 6) to the applied total nutrient (Table 1) for the main nutrients N, P, and K yielded the crop apparent nutrient recovery efficiency $RE_{N,P,K}$ as defined by Dobermann [40] (Table 7).

Table 7. Nutrient apparent recovery efficiency of Chinese cabbage plants from OF for N, P and K (%).

Treatment	N	P	K
N159	55	48	77
N317	37	20	50

If the existing 34 ha of *F. japonica* and *F. x bohemica* in Ljubljana (Figure 1a) were harvested for the production of OF, a yield of total fresh matter between 813 and 3060 t would be expected, depending on the yield of *F. japonica* (between 23.9 and 90 t ha^{-1} of fresh plants), which would yield ca. 924–3477 m^3 of OF product.

In line with Table 1, the applied nutrients with OF N159 (kg ha^{-1}) are comprised of 159 kg N ha^{-1}, 19 kg P ha^{-1}, and 100 kg K ha^{-1}, respectively. When considering an average crop uptake (kg ha^{-1}) of the selected crops [39], the produced OF would cover the N fertilizer needs of 67 ha to 247 ha, depending on the yield of *F. japonica* (between 23.9 and 90 t ha^{-1} of fresh plants). The maximum area potentially supplied with OF considerably surpasses the urban gardening area in Ljubljana (167 ha in the year 2010). These results indicate that OF could also be used in professional urban farming adjacent the city and could significantly contribute to the local nutrient cycle and food system (Table 8). It is evident, that OF produced from *F. japonica* contains on average two to three times more nutrients as taken off the garden land by vegetable crops. OF is especially rich in N and K (Table 8).

Table 8. Area (ha) potentially supplied with nutrients by *F. japonica* organic fertilizer produced on 34 ha when considering average crop uptake according to technological instructions for integrated vegetable production [39].

Potential Use of Organic Ferilizer	N	P	K
nutrients content in OF (% fresh matter)	1.59	0.19	1.00
F. japonica yield = 23.9 t ha^{-1}: total plant nutrients in OF (kg)	11,370	1359	7151
F. japonica yield = 90 t ha^{-1}: total plant nutrients in OF (kg)	42,816	5116	26,928
average crop uptake (kg ha^{-1})	170	58	221
Area potentially supplied with nutrients by OF in the case of average crop nutrient uptake (ha)	66–252	23–88	32–122
Unit of land fertilized with OF to cover nutrients uptake by the selected vegetables/unit of land for OF production	1.9–7.4	0.7–2.6	0.9–3.6

4. Discussion

F. japonica is known for its participation in numerous ecosystem services [19–22]. However, as an invasive species, it causes significant structural and functional changes in urban and rural ecosystems [1–5,8–10]. This research focused on the added value of *F. japonica* [19]. The rationale for this research was provided by Aguilera et al. [1], who indicated a high N uptake from the soil for *F. japonica*, which led us to assume the good N remobilization capacity of the produced organic fertilizer (OF) from *F. japonica*.

The fresh plant biomass harvested in this experiment, 23.8 t ha^{-1} was significantly lower than the 47 t ha^{-1} reported by Bernik et al. [37], who reported a harvest from an unmanaged patch. However, the plant material in this research was collected from a combination of unmanaged and managed one-month-old patches, which is why the green mass was less developed and less fresh plant biomass was harvested.

A fermentation process was used to produce an organic fertilizer, OF, from *F. japonica* using an innovative method of lactic fermentation by addition of EM Bokashi fermentation inoculum, complementary to some mechanical [11,16], biological [14], and combined approaches [41] already used to manage this invasive species.

Compared to classical aerobic thermophilic composting, fermentation has several advantages. The lack of aeration and mixing during the process; low energy input; further, no heat loss is produced, and no or few harmful gaseous compounds (e.g., CO_2, NH_3, and N_2O) are released into the air, and therefore more energy and plant nutrients remain in the fermented organic matter [26]. The high level of acidity in OF, together with the inclusion of a probiotic lactic-microorganisms consortia, was important to protect the material against further microbial degradation [42,43]. Furthermore, there is no loss of water-soluble K, as the fermentation process is conducted in a closed system where leaching does not occur [26]. Besides organic acids, secondary products are formed, such as enzymes, amino acids, and vitamins, which have a stimulating effect on both soil microorganisms and the cultivated crops [44]. Due to its production method, the C footprint of the fermented OF is lower than that of similar fertilizers (such as manure and compost), making OF an interesting alternative plant nutrient for reducing CO_2 emissions from agriculture [26,45].

Pathogenic microorganisms (e.g., *Escherichia coli* and bacteria of the genus *Salmonella*) in fermented OF, moreover, do not reproduce due to acid environment (pH of OF was 4.6), making OF a safe product from a human-health perspective [26]. The disadvantage of this treatment is that during fermentation, no high temperature is generated [26], which would destroy the seeds of *F. japonica* or inhibit their germination. Therefore, the plant material harvested for the production of OF should not include viable seeds or propagules with high reproductive capacity (with harvesting done in the flowering phase at the latest).

The experimental results prove the hypothesis that the OF produced from *F. japonica* could indeed successfully replace farmyard manure, which is not easily obtainable in urban environments.

The yields of Chinese cabbage mass of the whole heads obtained in fertilization experiments in some other studies are partially comparable to ours. Staugaitis et al. [46] achieved a similar yield of 50 t ha^{-1} with treatment N0 and 76 t ha^{-1} with treatment N225, although the Chinese cabbage variety and the pedo-climatic factors were not the same as those in our study. The same statistically significant differences in the masses of marketable heads were observed between treatment groups, as reported by Staugaitis et al. [46]. Dry matter content of Chinese cabbage plants was high, 9–11%, but comparable to the figures reported by Kosson et al. [47]. The variability observed reflects a combination of abiotic factors (climate) and the soil system [48–51]. Based on previous research it would be interesting to focus further research on changes in the soil that might occur when using OF for a longer period (several years). It would be interesting to explore how the nutritive value of OF changes with an altered collection of raw *F. Japonica* material for its preparation (different time of year) [48–50,52].

The fermented OF produced by *F. japonica* contained 2.5-times more ash in dry matter than raw substrate from *F. japonica* (Table 2) and showed a well-balanced composition of main plant nutrients due to its high N sequestering and remobilization ability [1], as well as due to lactic fermentation treatment, where no/little N losses occurred. The dry matter content in the OF was comparable to that of many composts and much higher than that in digestates [53]. The quantity of N in fresh lactic-fermented OF was relatively high compared to average cattle farmyard manure but on a comparable level to solid poultry, and rabbit manure [54,55]. In comparison to compost and digestates, the relative concentration of N in OF was found to be much higher [56].

The ratio of C/N in OF was relatively narrow (14.5:1), which indicates that N would be readily mineralized after incorporating the OF into the soil. According to Lazicki et al. [57], organic matter with a C/N ratio >19:1 leads to N immobilization, whereas organic matter with C/N ratios <14:1 mineralizes N. This result is comparable to C/N ratios in well-composted plant material and higher than the ratios in many biogas digestates [35].

Our results proved that after OF being applied and incorporated into the soil, the fermented organic matter was largely mineralized in the presence of oxygen and aerobic soil microorganisms, which resulted in high apparent N, P and K recoveries in Chinese cabbage yield (Table 7). For an organic fertilizer of plant origin the contents of P and K in Chinese cabbage were relatively high. The ratio in kg t^{-1} of fresh OF was in line with the needs of vegetable crops, which take up 4 to 8 times more K than P [58]. However, the concentration of K (%) in the Chinese cabbage heads achieved in our research with OF (2.65% K) was a bit lower to the research of Pokluda [59], where the average K was 3.1%, but this difference can be attributed to different pedo-climatic conditions.

Increasing yields due to increasing fertilization rates by OF accompany a certain dilution of N in plant biomass, which is due to the "law of diminishing yield increments". Consistent with the findings of Mitscherlich [60], the crop recovery efficiency decreases with an increase in fertilizer doses. The nutrient recovery efficiency is smallest for P and highest for K. Considering the large proportion of N initially organically bound in the OF, the recovery efficiency is shown here to be surprisingly high.

Studies reported that an average yield of Chinese cabbage (50 t ha^{-1}) [47] takes up 26 kg ha^{-1} P and 180 kg ha^{-1} K. In our research, with 10 t OF ha^{-1}, we supplied 10 kg P and 100 kg K. Here, the crop recovery efficiency $RE_{N, P, K}$ indicates the amount of (main) nutrient taken up by the crop and the remaining share in the soil. The crop directly took up quite a substantial fraction of the applied plant nutrients from OF (apparent recoveries for N159 were 55%, 48%, and 77% of N, P, and K, respectively), which is excellent for only two months of Chinese cabbage growth and to the amount expected for mineral N and K fertilizers. This result is even better than of mineral P-fertilizers, where the percentage recovery of fertilizer P calculated by the difference method normally ranges from 10 to 25% for a given crop in a given season [61]. However, surpluses, particularly those of water-soluble nitrate, can be leached after harvest. If Chinese cabbage is the last crop during the year, a catch crop should be cultivated (e.g., winter cereals) to retain the nutrients available for the crops in the following year.

It can be assumed that OF in soil quickly mineralizes, releasing readily available N for the cabbage. In this study, the cabbage was not grown long enough to capture all N mineralized, as readily available mineral N was detected in the soil right after harvest (Table 3). However, the soil mineral N after harvest was not elevated by OF application compared to the non-fertilized control, even under the highest N application, N317. Nitrate-N, which was the predominant mineral N formed in soil after the harvest, was high in content (32 to 34 mg NO_3-N/kg soil; Table 3), which indicates high mineralization capacity of the experimental soil. Despite the high N-mineralization potential of the soil, the N input from OF was able to match the dynamic needs of the Chinese cabbage for N (good apparent N efficiency; Table 8) and, consequently, achieved significantly higher yields without leaving excess mineral N in the soil after harvest compared to the Control, N0. This observation can be attributed to characteristic of OF: rather low C/N ratio, 14.5, and low content of fibers (lignocellulose), 8% (Table 3), of which all being favorable for net N mineralization.

Table 9 shows the modeled required application of *F. japonica* OF (1.59% N, 0.19% P, 1.00% K). We assumed garden soils with initial soil P and K supply in class C (optimal) and no plant-available mineral N readily available to meet the plant nutrient requirements of selected crops [38] at a given expected average crop production yield based on the integrated plant nutrient management guidelines [39]. Generally, N in OF was found to be the limiting factor among the main nutrients for plant growth. Moreover, the N availability for plants was significantly higher than that in comparable products [62]. Traditional organic fertilizers used in organic farming often contain a P concentration above plant needs, which leads to an accumulation of P in soils, particularly if fertilization is quantified according to the required plant needs for N [62].

Table 9. Required application of organic fertilizer (OF) from *F. japonica* (1.59% N, 0.19% P, 1% K; crop recovery efficiency for N 46%) for selected crops in non-marketable urban gardening in Ljubljana, Slovenia.

Crop	Yield	N			P			K			OF Required
		CU	FR	SCNR	CU	FR	SCNR	CU	FR	SCNR	
	kg/m²	g/m²	g/m²	%	g/m²	g/m²	%	g/m²	g/m²	%	kg/m²
green beans	0.8	7.0	7.0	100	4.0	0.8	38.5	15.0	4.4	54.0	0.8
lettuce	4.0	9.5	9.5	100	3.3	1.1	63.3	14.5	6.0	75.8	1.1
potatoes	2.5	10.0	10.0	100	3.5	1.2	62.8	15.0	6.3	77.1	1.2
onion	5.0	12.0	12.0	100	7.5	1.4	35.2	18.0	7.5	77.1	1.4
radicchio	2.0	12.0	12.0	100	3.0	1.4	87.9	13.0	7.5	106.8	1.4
parsley	2.8	13.0	13.0	100	4.5	1.6	63.5	16.5	8.2	91.2	1.5
zucchini	4.0	15.0	15.0	100	5.5	1.8	60.0	21.0	9.4	82.7	1.7
carrot	7.0	17.5	17.5	100	8.4	2.1	45.8	34.3	11.0	59.0	2.0
paprika	4.0	18.0	18.0	100	4.5	2.2	87.9	18.0	11.3	115.7	2.1
cucumbers	4.0	18.0	18.0	100	6.5	2.2	60.9	22.0	11.3	94.7	2.1
mangold	2.5	18.0	18.0	100	6.0	2.2	66.0	22.5	11.3	92.6	2.1
cabbage	5.0	24.0	24.0	100	6.5	2.9	81.2	28.0	15.1	99.2	2.8
tomatoes	11.0	32.0	32.0	100	6.0	3.8	117.3	30.0	20.1	123.4	3.7
pumpkins	10.0	32.0	32.0	100	11.5	3.8	61.2	42.0	20.1	88.2	3.7
AVERAGE	4.6	17.0	17.0	100	5.8	2.0	66.5	22.1	10.7	88.4	2.0

Abbreviations: CU—crop uptake (based on the expected yield following the Technological instructions for integrated vegetable production [50]), FR—fertilizer requirement (based on the fertiliser properties crop uptake), SCNR—supplied crop nutrient requirement (the percent of nutrients supplied from the required).

The crop recovery efficiency levels of N in our short-term experiment were 55% (N159) and 37% (N317), and the average N159-N317 was 46% (Table 8). OF, therefore, is a good source of N (under the condition that the organically bound N mineralizes as rapid as in the experiment), a moderate source of K, and a low source of P. In order to achieve an average yield of 5 kg/m^2 for the selected crops and to cover 100% of the N requirement of the crops, an application of 2 kg OF/m^2 would be necessary (Figure 4).

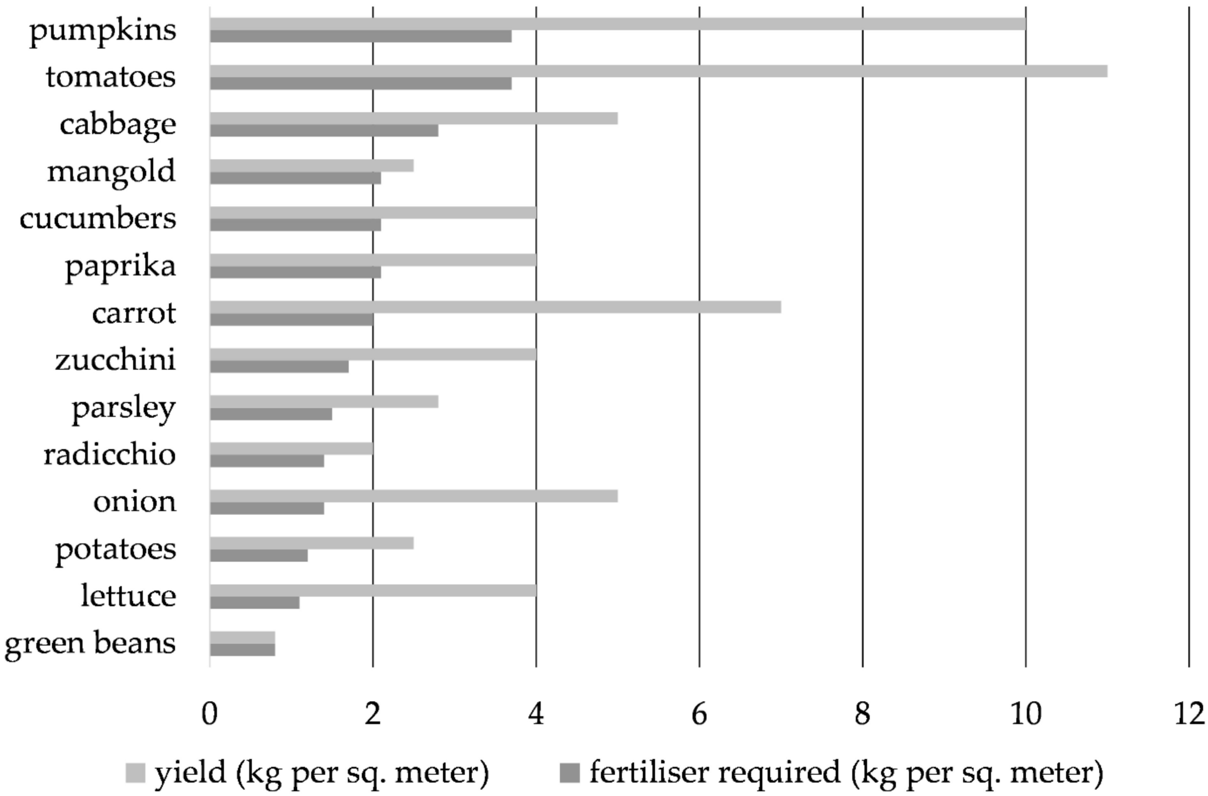

Figure 4. Required application of organic fertilizer (OF) (kg/m^2) from F. japonica (1.59% N, 0.19% P, 1% K; assumed recovery efficiency for N 46%) based on the expected yield, following the Technological instructions for integrated vegetable production [39] for selected crops in non-marketable urban gardening in Ljubljana, Slovenia, at a given expected yield (kg/m^2) reported by Glavan et al. [38].

This model application would cover 66.5% of P and 88.4% K average crop requirements (Table 9). For some of the more N-demanding crops, such as cabbage, pumpkins, and tomato, higher OF application of 2–3.7 kg/m^2 is needed to achieve the targeted yield. Full coverage of N requirements would result in P and K oversupply for tomato and K oversupply for radicchio and paprika but would undersupply crop P requirement for onion, green beans, and carrot (P supply < 60%) and undersupply the K crop requirements of green beans and carrot (K supply < 60%) (Table 9). Over the long run, some mineral fertilization could be applied to cover the gaps in the plant needs of P and K if mineral fertilization is permitted. Organic farming does not allow mineral N-fertilization but allows certain P- and K-fertilizers (which are not so strongly processed). In cases where P and K are oversupplied, vegetables with a longer growing season, as well as some of the plants grown as catch crops, possess the ability to access P and K resources from deeper soil layers [63].

OF fertilizer treatments (N159, N318) showed sufficient nutrient uptake to meet the needs of fast growing vegetables. However, Staugaitis et al. [46] warn that N applications greater than 180 kg ha^{-1} can negatively influence the inner quality of Chinese cabbage in terms of its content of vitamin C, nitrates, and soluble solids. This negative aspect of high N fertilization is more probable when soluble N fertilizers are used. In a case of OF, N is organically bound and is released gradually. Even with the application of 318 kg N/ha, the inner quality of our cabbage was not degraded.

In organic vegetable production, the nutrient recovery achieved with frequently used organic fertilizers is lower; the mineralization rate in the first year of application for organically bound N in solid manure is 10–30%, for poultry manure up to 45% [62]. Additionally, the nutrient dynamics after fertilization with OF should be further researched to explore nutrient dynamics under the repeated incorporation of OF in soil over several growing seasons and for different crops and soil conditions.

The approach adopted in this work was shown to be a viable alternative to manage the uncontrolled spread of *F. japonica* in urban areas. The OF production process is simple enough to be repeated by small urban farmers and has the potential to be reproduced on a larger scale, by waste management companies. In this study, plant materials for the production of OF were cut and collected by hand. A more mechanized approach could be applied for the larger condensed *F. japonica* patches that typically occur along the banks of highways, especially when the plants are mowed at least twice per year [64]. This would ensure a high green-mass yield and an interruption in the reproductive cycle of the plant (pollen drift and seed formation) at the stage when the plant N content is expected to be highest, although precaution is necessary as some metallic trace elements, such as Zn, can transport to aboveground parts of *F. japonica* [65]. The approach taken in this study seems to be able to complement frequent (weekly) management of *F. japonica* stands in parks, nurseries and riverbanks, where frequent cutting [11] continues to be applied as a means of suppressing *F. japonica*, although the long-term success of frequent mowing of *F. japonica* as a management method remains to be proven [66].

5. Conclusions

The use of the green parts of *F. japonica* to produce organic fertilizer OF not only opens up the possibility of preventing the rapid spread of the plant, but also provides new ideas for its use. There are essentially no experiments on the usefulness of organic fertilizers from *F. japonica* in vegetable production. The results of the present study, the first experiment in this field are of international significance as they not only demonstrate OF production by fermentation but also evaluate OF's fertilizer value.

The disadvantages of this technically simple experiment are its low number of repetitions and use of untypical soils with a comparatively large supply of N. In the future, this experiment should be repeated with more treatments over a longer period and on different soil types. In addition, an experiment should be carried out on different crops to determine the possible negative effects of OF's properties on some vegetable species. Instead of inoculation with EM Bokashi, it should be tested if an inoculum from previous fermentation could be used to reduce costs.

To better assess the economic potential of the OF fertilizer, it is also necessary to evaluate the possible reluctance of growers to use fertilizer from invasive plants. In this area, research involving a wide range of end-users, from hobby to market producers, should be carried out. The proposed activities are relevant to the issue of society's attitude towards invasive species and support the advocacy for the management of invasive plant species in the light of the circular economy.

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