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Application of Digestate from a Methane Fermentation Process for Supplying Water and Nutrients in Sweet Potato Cultivation in Sandy Soil

Yoshiaki Kitaya [1,*], Siqinbatu [2], Ryosuke Endo [2] and Toshio Shibuya [2]

[1] Organization for Research Promotion, Osaka Metropolitan University, Gakuencho 1–1, Osaka 599-8531, Japan
[2] Graduate School of Agriculture, Osaka Metropolitan University, Gakuencho 1–1, Osaka 599-8531, Japan; endo_r@omu.ac.jp (R.E.); tshibuya@omu.ac.jp (T.S.)
* Correspondence: kitaya@omu.ac.jp

Abstract: To develop technology to efficiently utilize digestate from methane fermentation in agricultural production, the application of digestate from methane fermentation for supplying nutrients in sweet potato cultivation was investigated in sandy soil. Different strengths of diluted digestate with water were applied to sweet potato plants as water and nutrient supplies to determine the appropriate strength of digestate from methane fermentation for sweet potato production in sandy soil. The growth of sweet potato cultivated with diluted digestate was also compared with that of sweet potato cultivated with a commercial chemical nutrient solution. The growth rate of the tuberous roots with the strength of 1/20 of the digestate was greatest among the treatments with different digestate strengths (1/80–1/2) and commercial nutrient solutions (1/4–1). Consequently, we proposed a sweet potato production system using a bottom irrigation method with digestate from methane fermentation, which will be applicable in semiarid regions. In conclusion, the results of this study can be effectively used in a regional agricultural system combined with a methane fermentation system and can contribute to increasing food production as well as the establishment of a resource recycling society.

Keywords: agriculture; methane fermentation; nitrogen fertilizer; resource recycling; sweet potato

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1. Introduction

Methane fermentation is a biomass conversion technology [1–4] that degrades organic matter such as carbohydrates, proteins, and fats biologically through anaerobic processes, which include hydrolysis, acidogenesis, acetogenesis, and methanogenesis, to produce biogas (generally 60–70% CH_4, 30–40% CO_2, and low amounts of other trace gases), which is a promising source of renewable energy [5–7].

Recently, methane fermentation by using biomass resources as industrial waste has been promoted because methane fermentation with organic residues and wastes is one of the most attractive renewable energy production technologies for reducing greenhouse gas emissions, as well as for reducing the environmental load of organic waste.

Therefore, methane fermentation technology has received increasing interest as one of the most promising technologies for recycling organic wastes containing a large amount of water, such as raw garbage and livestock manure. This technology is expected to be widely used to promote the recycling of organic waste, especially in large cities where a large amount of organic waste is generated. When we attempt to spread this technology in large cities, one significant obstacle is that there are not enough agricultural fields for applying the digestate in large cities and their suburbs. Additionally, transportation of the raw digestate to distant agricultural fields is not feasible because of the high associated costs [8]. Moreover, large storage tanks are often needed because the demand for digestate is seasonal according to plant cultivation schedules. On the other hand, it is costly and problematic in material circulation to treat the digestate for discharge in accordance with legal requirements.

In this context, it is necessary to develop efficient digestion methods, especially for fertilizer or soil improvement, for agricultural fields [9–11] reviewed practical digestate applications to agricultural fertilization as soil applications.

An explosive increase in population has advanced worldwide. The shortage of food accompanying the rapid increase in population has become a serious problem in many countries. The promotion of food and feed production, therefore, has become an urgent issue in these countries.

In agriculture, reconsideration of the usual agricultural system and system construction of sustained agricultural production based on resource circulation is necessary. In particular, a reduction in the consumption of exhaustible resources such as chemical fertilizers and agrichemicals and a decrease in environmental load are needed. The areas with problems with the disposal of industrial waste from the livestock industry, agriculture, and food production have increased. Therefore, the use of methane fermentation technology for the circulation of organic waste is notable.

Most of the digestate, a byproduct of methane fermentation, is discharged through treatment based on an environmental assessment [12]. The effective use of methane fermentation, which involves many nutrient components, as a liquid fertilizer for digestate has been attempted in agriculture, but its application is currently limited [13]. The characteristics of digestate from methane fermentation include the presence of many nitrogen and potassium components and a small amount of phosphorus. Additionally, most nitrogen is nitrogen in the form of ammonia [14,15]. Efficient use of digestate is necessary according to the appropriate application design and water regimen when digestate is applied as a nutrient solution. On the other hand, the digestate from methane fermentation may cause the cost of the fertilizer to change due to distinctive circulating resources.

However, the following problem is indicated for the use of digestate because the properties of digestate are different from those of the raw material biomass. The nitrogen in the digestate mainly consists of ammonia, and this is a fast–acting fertilizer used as an NK nutrient. It is thought that nitrification of NH_4–N in digestate occurs more quickly than in chemical fertilizer. Since the digestate contains intact raw material, solid–liquid separation of the digestate is necessary [16].

There are many previous studies on the application of digestate to horticultural crops. For example, tomato plants are of equal or greater quality and yield when water is supplied with digestate than when water is supplied with conventional chemical nutrients [17–19]. However, very few studies have quantitatively investigated the effects of digestate on sweet potato plants. We focused on the use of digestate as a nutrient solution for sweet potato production in arid and semiarid regions.

Among root crops, sweet potato is the second most widely cultivated crop in the world after potato, and it is the largest tuber crop in Asia [20]. Sweet potato plants will play an important role in solving global issues regarding food, natural resources, and the environment in the 21st century because sweet potato is a promising raw material for biofuels and biodegradable plastics, as well as food, animal feed, and industrial materials for producing starch, sugar, and alcohol.

Compared with other crops, sweet potato potentially fixes a relatively large amount of energy (for example, 194 MJ ha^{-1} d^{-1}), and its ability to yield under poor soil conditions has contributed to its role as a food security crop in many regions [21]. The leaves, petioles, and stems of some sweet potato varieties are edible and palatable, as are the tuberous roots, and can be utilized as fresh leafy vegetables. The sweet potato is an excellent source of natural health–promoting compounds, such as β–carotene and anthocyanins, which are functional foods that contain antioxidant elements and staple foods rich in starch and protein [22]. In addition, the sweet potato is considered an environmentally friendly crop because it requires a small amount of fertilizer and other agricultural chemicals and is temporarily tolerant to stressful environmental conditions, such as typhoons, drought, and concentrated rainfall.

The goal of this research is to develop a recycling–oriented society by combining methane fermentation facilities with agriculture. Furthermore, in the future, by generating electricity using the biogas produced in methane fermentation facilities, in addition to using electricity, the exhaust heat generated during the process can be used to heat agricultural greenhouses and dry and process agricultural products, which will enable the efficient use of energy and the reduction in greenhouse gas emissions, along with the treatment of local organic waste. In other words, the introduction of methane fermentation facilities into agriculture is expected to lead to the efficient use of energy and the realization of a recycling–oriented society, as well as the revitalization of the local economy.

This research is in an early stage of research aimed at the above goal. We developed a technology for the effective use of digestate from methane fermentation to supply water and nutrients in sweet potato cultivation. To obtain fundamental information on the optimum concentration of digestate for sweet potato cultivation, we examined the different strengths of diluted digestate and investigated the growth performance of sweet potato plants in sandy soil.

2. Materials and Methods

2.1. Preparation of Plant Materials

Sweet potato (*Ipomoea batatas* (L.) Lam, cv. 'Beniazuma') was cultivated in a plastic house with fully open side windows under simulated dry conditions in Osaka, Japan. The nursery plants were established for two weeks via cuttings before transplanting for the test.

2.2. Raw Material of the Methane Fermentation Digestate

The digestate was collected at a methane fermentation facility in Yagi town, Kyoto, Japan. The source mainly contained cattle manure, which was fermented with a methane gas yield of 62.8 $m^3\ d^{-1}$. Commercial chemical nutrient solutions (Otsuka nutrient solution A formula, Otsuka Agri Co., Tokyo, Japan) were also used as standard chemical nutrient controls.

The original digestate from methane fermentation was left to stand for one week to separate the solid matter, and the supernatant without visible solid particles was used as the experimental solution. The EC and pH were measured using an EC meter (1772522, Azuwan Co., Osaka, Japan) and a pH meter (pH/ION METER D–53, HORIBA Co., Kyoto, Japan), respectively. The ion concentrations of the nutrient solutions were measured using an ion chromatograph (LC–10Advp, SHIMAZU Co., Kyoto, Japan). The relative chlorophyll content in the leaves was measured using a chlorophyll meter (SPAD–502 Plus, KONIKA–MINORUTA Co., Tokyo, Japan) as an index of photosynthetic capability.

The EC, pH, and ion concentrations of the digestate from methane fermentation (hereinafter abbreviated as MFD) and the commercial chemical nutrient solution (hereinafter abbreviated as CNS) are shown in Table 1.

Table 1. Properties of the original methane fermentation digestate (MFD) and commercial chemical nutrient solution (Otsuka formula A) (CNS).

Solution Medium	EC ($mS\ cm^{-1}$)	pH	NO_3^-–N ($mg\ L^{-1}$)	NH_4^+–N ($mg\ L^{-1}$)	K^+ ($mg\ L^{-1}$)	Na^+ ($mg\ L^{-1}$)	PO_4^{3-} ($mg\ L^{-1}$)	SO_4^{2-} ($mg\ L^{-1}$)
CNS	2.52	6.7	230	34	368	238	134	224
MFD	31.0	8.1	–	2787	3311	447	638	332

'–' indicates no detection.

2.3. Determination of Suitable Digestate Concentration

Sweet potato was cultivated for 134 days from the middle of June to early November in the plastic house. The nursery plants were transplanted to bottomless plastic pots (20 cm diameter, 35 cm height, each) filled with sandy soil to imitate fine sand in the semiarid region (Figure 1).

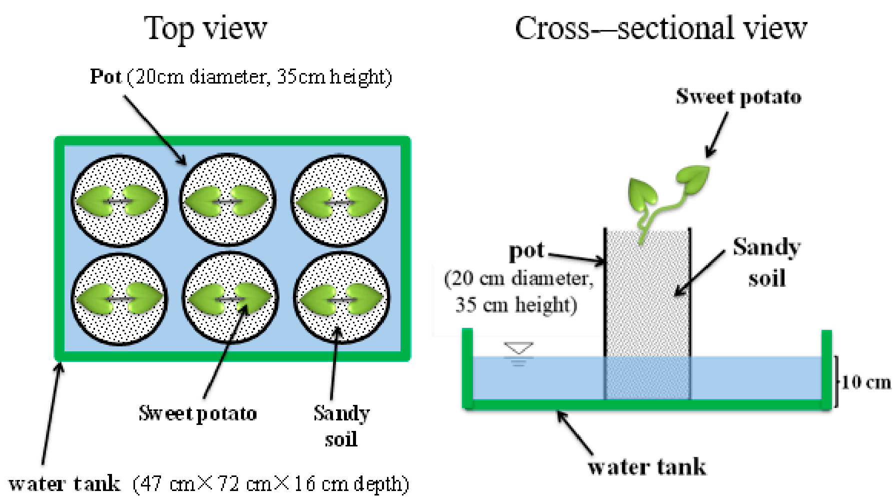

Figure 1. Schematic diagrams of the experimental cultivation system for investigating suitable MFD dilutions.

The MFD solutions were diluted to 1/2, 1/10, 1/20, 1/40, and 1/80 with water to supply the nutrient solution to the plants. Additionally, CNS solutions diluted to 1/1, 1/2, and 1/4 strength with water were subjected to comparative experimental treatments.

Each pot was placed in a water tank, and each nutrient solution was added to the water tank at a depth of 10 cm, as a water table 25 cm below the soil surface in the pot was formed (Figure 1).

The experimental cultivation system was placed in the plastic house (Figure 2). The mean air temperature and relative humidity monitored hourly in the plastic house were 33.9 ± 5.1 °C (mean ± SD) and 50 ± 16%, respectively, during the day.

Figure 2. Photo of the experimental setup in the plastic house.

2.4. Assessment of the Feasibility of Sweet Potato Cultivation with Digestate from Methane Fermentation

We examined a practical cultivation system using digestate from methane fermentation based on the results of the abovementioned experiment. Sweet potato plants were grown for 144 days, from the middle of June to the middle of November, in a plastic house with fully open side windows under simulated dry conditions. Sweet potato cultivated in two cultivation containers (4.5 m (L) × 0.3 m (W) × 0.3 m (H)) filled with sand to imitate sandy soil in the semiarid region of Inner Mongolia. Sweet potato was also planted around the container to prevent surrounding effects. A 20–fold dilution of the digestate (EC:

1.5 mS cm^{-1}) was supplied from the container bottom as a water table 25 cm below the soil surface (Figure 3).

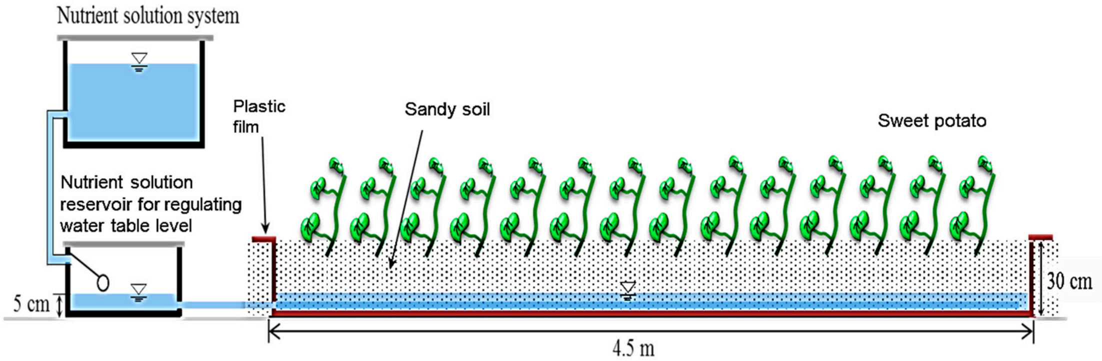

Figure 3. Apparatus for assessing the feasibility of using a sweet potato cultivation system with bottom irrigation in sandy soil in a plastic greenhouse.

The mean air temperature and relative humidity monitored hourly in the plastic house were 35.9 ± 5.5 °C (mean ± SD) and 46 ± 18%, respectively, during the day.

3. Results

3.1. Determination of a Suitable Digestate Concentration

The pH of each nutrient solution ranged from 6.0 to 6.7 and 8.0 to 8.2 in the CNS and MFD treatments, respectively, regardless of the dilution rate. The pH of the nutrient solutions based on MFD was greater than that of the nutrient solutions based on CNS. The growth performance of the sweet potato plants is shown in Table 2. The dry mass of the tuberous roots in the MFD×1/20 treatment tended to be the greatest among all the treatments. The dry mass of the tuberous roots in the CNS×1/2 treatment tended to be greatest in the CNS treatment. The dry mass of the tuberous roots in the MFD×1/20 treatment was 1.3 times greater than that in the CNS×1/2 treatment. In the MFD treatments, the relative chlorophyll content in leaves (SPAD value) increased with decreasing dilution up to MFD×1/20 and decreased beyond that level. The root system, including the tuberous roots, was visibly more vigorous in MFD×1/20 than in CNS×1/2 (Figure 4).

Table 2. Growth parameters of sweet potato plants cultivated in treatments with diluted methane fermentation digestate (MFD) and commercial chemical nutrient solution (CNS) for 134 days.

	Dry Mass (g/plant)								
	Leaves (a)	Stems (b)	Shoot (a + b)	Fibrous Roots (c)	Tuberous Roots (d)	Roots (c + d)	Total (a + b + c + d)	Shoot/Roots	SPAD
MDF×1/80	8.4	22.9	31.3	10.4	74.6	85.0	116.3	0.37	38
MDF×1/40	19.2	40.9	60.1	13.4	108.2	121.6	181.7	0.49	40
MDF×1/20	27.7	50.5	78.2	18.0	167.1	185.1	263.3	0.42	50
MDF×1/10	30.5	41.6	72.1	6.4	30.0	36.4	108.5	1.98	32
MDF×1/2	2.6	3.7	6.3	7.1	–	7.1	13.4	0.89	23
CNS×1/4	23.8	67.4	91.2	16.9	116.7	133.6	224.8	0.68	43
CNS×1/2	23.7	85.8	109.5	13.1	133.7	146.8	256.3	0.75	45
CNS×1	11.4	70.3	81.7	13.8	55.7	69.5	151.2	1.16	41
LSD*	13.6	35.8	45.2	14.1	55.2	65.3	107.7	0.14	5

LSD*: Least significant difference at the 5% level according to the Tukey–Kramer multiple comparison test. (n = 6).

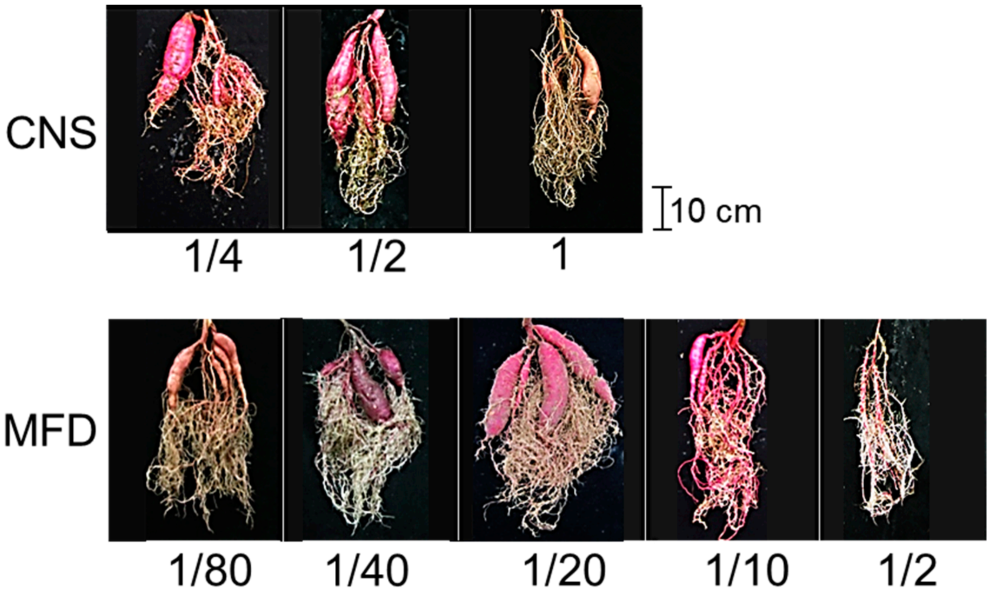

Figure 4. Representative underground parts of sweet potato cultivated in treatments with diluted methane fermentation digestate (MFD) and commercial chemical nutrient solution (CNS).

The shoot dry mass to root dry mass ratio (Shoot/Root ratio) tended to increase in denser nutrient solutions in both the MDF and CNS treatments. This means that the denser nutrient solutions promoted shoot growth more than root growth.

The actual EC values in the solution in the sandy soil were 0.5, 0.8, 1.5, 3.0, and 15.4 mS cm^{-1} for the 1/80, 1/40, 1/20, 1/10, and 1/2 strengths of MFD, respectively, and 0.7, 1.3, 2.5 (mS cm^{-1}) for the 1/4, 1/2, and 1/1 strengths of CNS, respectively. The dry mass yield of the tuberous roots tended to increase up to an EC of approximately 1.5 mS cm^{-1} and decreased beyond that level regardless of MFD or CNS (Figure 5).

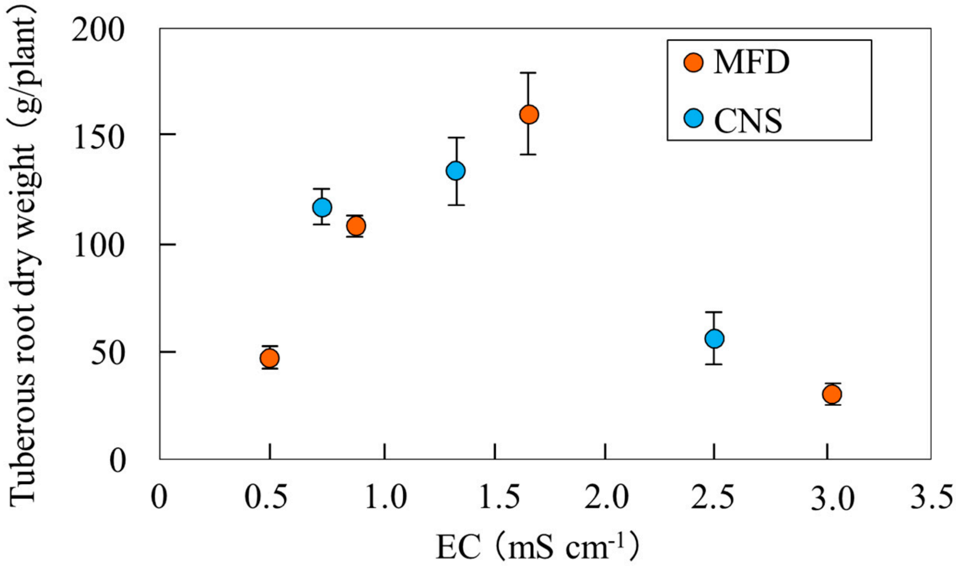

Figure 5. Effects of EC in sandy soil on the dry mass of sweet potato in treatments with diluted methane fermentation digestate (MFD) and commercial chemical nutrient solution (CNS). The error bars indicate the standard deviations (n = 7).

3.2. Assessment of the Feasibility of Sweet Potato Cultivation with Digestate from Methane Fermentation

The dry mass of the tuberous roots peaked at MFD×1/20 in the MFD treatment and at CNS×1/2 in the CNS treatment. The canopy of sweet potato plants grown for four months in the greenhouse is shown in Figure 6. The dry mass of the tuberous roots of sweet potato was significantly greater in the MFD×1/20 treatment than in the CNS×1/2 treatment, although the dry masses of the leaves and stems were significantly greater in the CNS×1/2 treatment than in the MFD×1/20 treatment (Figure 7). Tuberous roots were visibly more vigorous in MFD×1/20 than in CNS×1/2 (Figure 8). The fresh yield of sweet potato tuberous roots was 698 g m^{-2}/plant, which corresponds to 2.1 kg m^{-2} based on the results of this experiment at a planting density of 3 plants m^{-2}. This tuberous root yield was mostly the same at the stranded planting density (3–4 plants m^{-2}) for plants of the same variety in Japan.

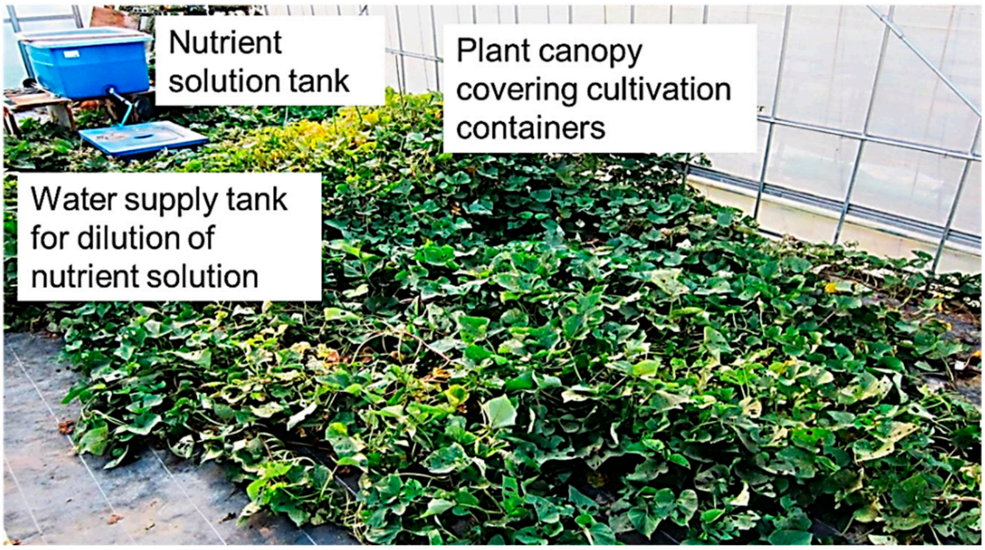

Figure 6. Photo of sweet potato grown for four months in the greenhouse.

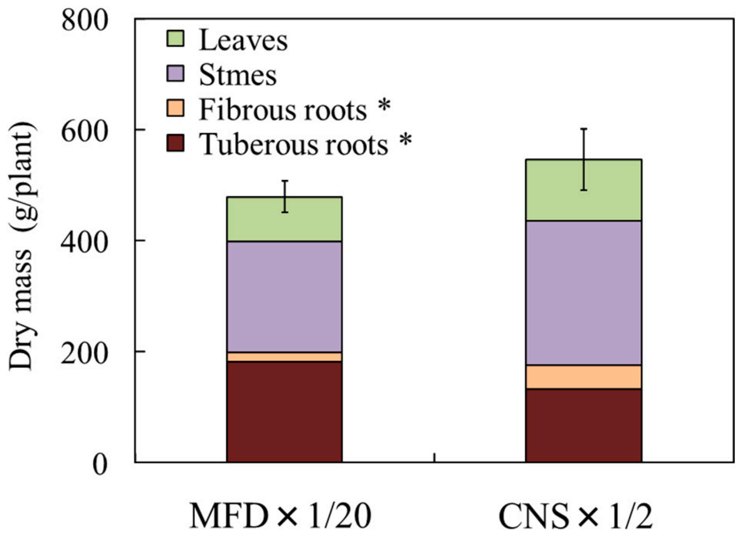

Figure 7. Effects of nutrient type on the dry weight of sweet potato plants grown in sandy soil with a bottom irrigation system supplemented with diluted methane fermentation digestate (MFD) and commercial chemical nutrient solution (CNS) for 144 days. The error bars indicate the standard deviations of whole plants (n = 7). An asterisk (*) on the right shoulder of the legend indicates a significant difference ($p < 0.05$) according to Student's *t*–test.

Figure 8. Representative underground parts of sweet potato cultivated on ridges with a bottom irrigation system with diluted methane fermentation digestate (MFD) and commercial chemical nutrient solution (CNS).

4. Discussion

The results of this study indicate that digestate is effective for the growth of sweet potato plants in ridges with bottom irrigation systems. Therefore, it is expected that sweet potato cultivation due to the supply of water and nutrients from digestate would be possible in the fields of semiarid regions, which consist of sandy soil with a fine particle distribution. Figure 7 shows that the formation of tuberous roots was greater with the application of the digestate solution than with the application of the commercial nutrient solution. Therefore, the digestate used in this study is a useful nutrient solution for sweet potato cultivation.

Sawicka et al. [23] reported that an increase in dry mass yield was observed when nitrogen fertilization was applied in the form of compost up to a level of 100 kg ha^{-1}, but above this level, the value of this trait decreased. In our study, although the method of nitrogen fertilization was different from that described above, the dry mass yield similarly increased up to a certain level of nitrogen fertilization and decreased beyond that level (Figure 5).

When digestate is used as a nutrient solution, one of the problems encountered is that it contains an excess amount of ammonium ions (NH_4^+) [10,24,25] produced by the degradation of proteins under anaerobic conditions [26]. This leads to toxicity in many plant species, although NH_4^+ toxicity can be alleviated by the coproduction of nitrate ions (NO_3^-) [27,28]. Therefore, it is necessary to convert NH_4^+ into NO_3^- in the digestate before applying the material to sweet potato cultivation. Nitrification, which is the biological conversion of NH_4^+ to NO_3^-, can be used for this purpose [29,30]. Botheju et al. [24] reported that approximately 75% of NH_4^+–N in digestate was removed in a sequential batch reactor process primarily through the conversion of NH_4^+–N to NO_3^-–N. However, research on the nitrification of digestate with other nitrification processes (for example, fixed–bed reactors and moving–bed biofilm reactors) is limited.

In this cultivation system, the regulation of water table levels is important. In soil, CO_2 is produced by microorganisms and root respiration. Generally, CO_2 is released through the soil surface through the ventilation path from the soil to the atmosphere, but excessive soil moisture blocks this ventilation path and increases the CO_2 concentration in the soil. In particular, digestate, which contains a large amount of organic components in addition to N components, increases the activity of microorganisms and promotes CO_2 production. Elevated CO_2 concentrations in the root zone associated with elevated soil water contents suppress the growth and tuberous root development of sweet potato plants [31]. Negative effects of high soil CO_2 concentrations on the growth of sweet potato plants have been reported [32]. When producing sweet potatoes, it is important to manage the water supply to ensure sufficient water content and low CO_2 concentrations in the soil. With the application of the soil ridge culture method with a bottom irrigation system, it is expected that the tuberous root production of sweet potato plants will increase by controlling the soil ridge height to maintain a sufficient distance from the water table to the soil surface to maintain 10–15% of the volumetric water content and low CO_2 concentration in the root zone soil [31]. Therefore, excessive soil moisture conditions must be avoided even in bottom irrigation systems.

Previous studies have reported the results of applying MFD using different substrates to different crops. For example, Barzee et al. [17] reported that the highest yield of tomatoes was obtained with dairy manure digestate fertilizer followed by food waste digestate fertilizer and mineral N fertilizer. Doyeni et al. [33] reported an increase in nitrogen use efficiency and positive effects on the grain yields of spring wheat, triticale, and barley with the application of animal waste digestate. Takemura et al. [34] investigated the changes in the concentrations of plant macronutrient ions in nitrified digestate from methane fermentation using food waste as a substrate and reported the usefulness of nitrified digestate for improving the growth performance of chrysanthemum cultivated on rockwool substrates.

In this study, we did not evaluate the substances contained in the plant body. Lee et al. [35] reported that, compared with chemical fertilizer application, MDF application increased the antioxidant capacity, total phenolic content, and ascorbic acid content in kale plants, while legume plants showed conflicting results in terms of nutrient levels. The effect of MDF on the nutritional components of sweet potato is an important topic for future research.

As a future challenge, by increasing the amount of water input through the supply of some of the water conventionally used for irrigation to the methane fermentation process, the following benefits could be obtained by diluting the input substrate raw material. (1) The appropriate substrate concentration is maintained, which increases the activity of the fermentation bacteria, stabilizes the fermentation process, and improves the methane gas yield. (2) The stabilization of the fermentation process reduces the concentration of solid substances in the fermentation residue, simplifies the process of making it into liquid fertilizer, and improves its quality as a fast–acting fertilizer. In addition, the cultivation of water–deficit–resistant sweet potato varieties [36] can lead to even more water–saving irrigation.

We propose a sweet potato production system involving a bottom irrigation method with digestate from methane fermentation, as shown in Figure 9, which will be applicable in semiarid regions. The system can be applied to other root crops and leafy and fruit vegetables. The results of this study might contribute to the establishment of a resource recycling system, including regional agricultural and human habitation systems, and to the supply of healthy food ingredients, especially in semiarid regions where fresh vegetables are scarce.

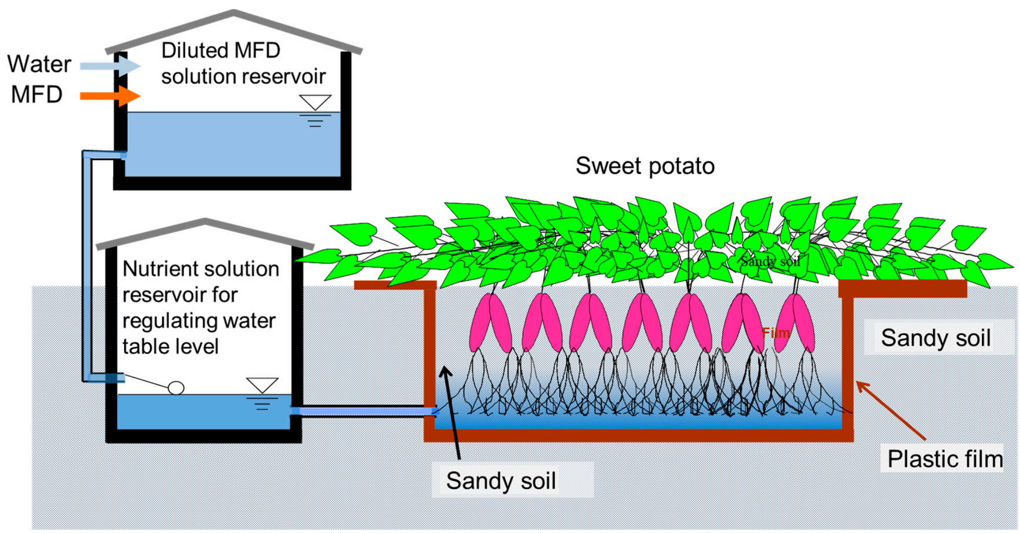

Figure 9. Schematic diagram of sweet potato cultivation based on bottom irrigation with diluted methane fermentation digestate (MFD) in semiarid regions.

5. Conclusions

The application of MFD, which includes inorganic nutrient salts as nutrient constituents, as a liquid nutrient in sweet potato cultivation was attempted. Consequently, digestate, a byproduct of methane fermentation based on biomass waste treatment, was confirmed to become a nutrient solution for sweet potato production. We demonstrated that the dilution of MFD at an appropriate concentration is suitable for sweet potato cultivation, and the yield of sweet potato was similar to or greater than that of chemical nutrients. The maximum yield of the tuberous roots of sweet potato was achieved at a 20–fold dilution ratio of MFD.

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