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Effects of Sewage Treatment Water Supply on Leaf Development and Yield of Tuberous Roots in Multilayered Sweet Potato Cultivation

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Abstract: To develop a way to mass-produce sweet potatoes (*Ipomoea batatas* (L.) Lam.) as an energy crop to replace fossil fuels, the effects of using a sewage supply as a fertilizer and heat source were investigated. When 25 pots planted with sweet potato vine seedlings were arranged in three layers and cultivated for 160 days from June to November by supplying treated sewage to the root zone, the yield of tuberous roots reached 19.5 kg m^{-2} due to the massive growth of leaves. In addition, when sweet potato seedlings were replanted in December and treated sewage was supplied to maintain the irrigation water temperature above 15 °C even in winter, overwintering cultivation was successful and 8.4 kg m^{-2} of tuberous roots were harvested in July. As a result, the annual production rate for 12 months increased to 25.3 kg m^{-2}, about 10 times the national average of 2.4 kg m^{-2} for open-field cultivation. The results far exceed previously reported maximum production of resource crops, such as sugarcane and eucalyptus, suggesting that the mass production of sweet potatoes by supplying treated sewage could provide an alternative to fossil fuels on a large scale.

Keywords: energy crop; *Ipomoea batatas*; overwinter cultivation; rhizosphere irrigation; sewage fertilizer

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1. Introduction

Sweet potato is produced mainly in Asian and African countries as a major food crop [1–3] and biofuel resource [4,5]. Not only are sweet potatoes a high-yielding crop, with nearly twice as many calories per cultivated area as rice and wheat [6], but their stems and leaves are also edible [7], so they can be easily converted to methane by microorganisms. Therefore, mass production of sweet potatoes is attracting attention as a fuel crop for biogas production [8,9].

When sweet potatoes that grow in half a year are converted to methane and used for cogeneration of electricity and hot water [10], the conversion rate of solar energy is expected to increase dramatically compared to the conventional method of using woody biomass, which takes more than 50 years to grow [11], for low-efficiency thermal power generation [12,13].

On the other hand, although sweet potatoes have higher productivity and yield than rice and wheat, they have a relatively low light-saturation point, so it is estimated that about half of the solar radiation on a clear day is unused [14,15]. Therefore, in order to increase the light-receiving area of leaves and increase the utilization rate of sunlight, a three-layer-cultivation method for sweet potatoes was devised and achieved a productivity of 10 kg m^{-2}, which is 4.4 times that of conventional farming, which uses the rhizosphere irrigation method [16]. As a result, it was suggested that it would be possible to produce large quantities of sweet potatoes domestically, which would be needed to replace all of the oil, coal and natural gas consumed in Japan.

Meanwhile, Russia's invasion of Ukraine highlighted the problems of fertilizer that lurked in Japanese agriculture. While Japan has relied on imports for most chemical fertilizers, Russia, Ukraine and Belarus are the main suppliers of K fertilizer, N fertilizer and feed crops [17]. This situation has made it difficult to import chemical fertilizers from abroad, and there is a strong desire to expand the use of domestic fertilizer resources such as sewage sludge [18–20].

In order to mass-produce sweet potatoes for food and fuel in the country, it is essential to procure large quantities of cheap fertilizer and recycle them. On the other hand, the population penetration rate of sewage treatment in Japan reached 92.6% in 2021 [21], and since most of the fertilizer component of the food ingested is excreted from the human body and accumulated in sewage treatment plants, it is expected that most of the fertilizer component needed for food production can be recovered.

Research on the use of treated sewage [22,23] and dried sludge [24,25] as a fertilizer has been conducted worldwide. Recently, the widespread use of hydroponic cultivation has also brought attention to the use of treated sewage as liquid fertilizer for the sustainable use and recycling of fertilizer ingredients [26].

In open-field farming, it is difficult to reduce the consumption of fertilizer because large amounts of fertilizer are generally supplied and surplus fertilizer on farmland is washed away or discarded without recovery [27,28]. Hydroponic cultivation, on the other hand, is expected to maintain an optimal supply of liquid fertilizer and increase the effect of fertilizer application, thereby significantly reducing the amount of fertilizer needed and making it easier to recover and reuse unused fertilizer components [29,30].

Moreover, since the water temperature of sewage and treated water rarely falls below 15 °C even in the winter [31,32], it is also expected to be used as a heat source for winter rhizosphere irrigation. Since sweet potatoes are difficult to grow at temperatures below 15 °C [33,34], it is common to plant them in spring and harvest them in autumn. Furthermore, in the warm, humid climate of spring and summer in Japan, sweet potatoes do not flower or bear seeds [35]. Therefore, in general agriculture, some of the tuberous roots harvested and stored in autumn are planted in the greenhouse from around February, and the leaves and stems are collected and planted as vine seedlings from around April. For this reason, not only is solar energy not available for more than half a year, including winter, but during the first month after planting seedlings, there are few leaves and the photosynthetic efficiency is extremely low.

In other words, if the leaves and stems harvested in November [16] can be planted as new vine seedlings and allowed to overwinter using warm sewage, the annual rate of solar energy use could double, eliminating the need for tuberous root storage and greenhouse heat sources to grow seedlings. As a result, it is expected to be possible to significantly improve the photosynthetic yield of sweet potatoes and reduce CO_2 emissions by substituting fossil fuels.

Against this background, the effect of sewage fertilization was studied to increase the annual production of sweet potatoes.

2. Materials and Methods

2.1. Rhizosphere Irrigation Supply of Sewage and Treated Sewage

The rhizosphere hydroponic cultivation of sweet potato using sewage was carried out at the southern sewage treatment plant in Iwata City (Shizuoka, Japan). Figure 1 shows the process of treating 73,000 $m^3 d^{-1}$ of sewage for 132,000 of the city's population using an activated sludge process. The inflow sewage always contains approximately 180 ppm of BOD (Biochemical Oxygen Demand) and approximately 190 ppm of SS (Suspended Solid), which are reduced to below the environmental limit of 15 ppm during the treatment process. The outline of various components based on periodic water quality inspection reports are also shown in the figure. Inflow sewage also contains fertilizer components, such as nitrogen (N) and phosphorus (P), most of which are removed using biological treatment in an aeration tank.

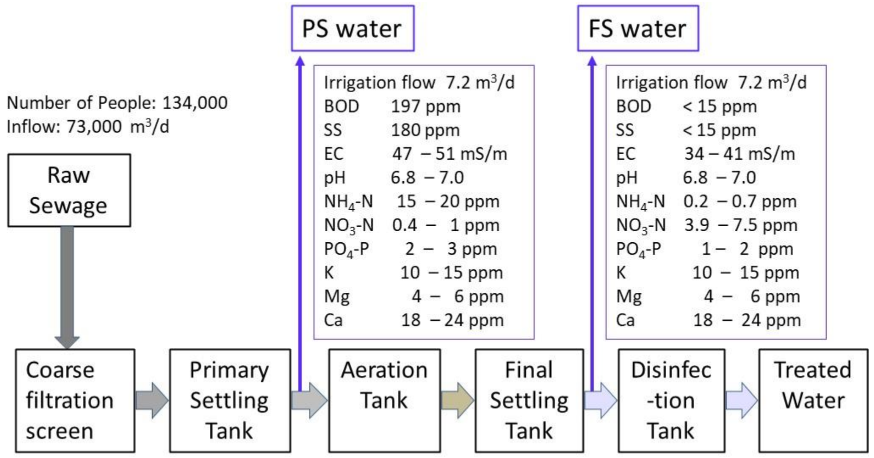

Figure 1. Sewage treatment process at Iwata City Southern Purification Plant and acquisition route of PS and FS water for sweet potato root zone irrigation and the outline of various components based on periodic water-quality inspection reports.

To supply sewage as liquid fertilizer to irrigate the rhizosphere of sweet potatoes, water introduced from the primary settling tank (PS water) was used as nutrient-rich raw sewage after sediment was removed from the incoming sewage, and water introduced from the final settling tank after aeration treatment (FS water) was used as treated sewage. Irrigation pipe drainage was returned to each sedimentation tank. The sewage flow rate was set at 7.2 m^3 d^{-1} and the dilution rate of the irrigation pipe at 6.0 h^{-1}.

Commercial horticultural liquid fertilizer (LF) was also used as LF water for comparison. The LF water composition was the same as that in a previous report [16].

2.2. Three-Layer Cultivation System

Sweet potato (*Ipomoea batatas* (L.) Lam.) cultivars *Suikenkintoki* (SK) and *Beniharuka* (BH) were used. Commercial vine seedlings of sweet potatoes were purchased in the same way as general farmers, planted in each pot in early June, grown for 160 days and harvested in early November.

This study used the three-layer culture system shown in Figure 2, which was the same as that used in a previous report [16]. The three-layer, 25-pot cultivation system occupied an area of 1.8 m^2 and retained irrigation water of about 50 L.

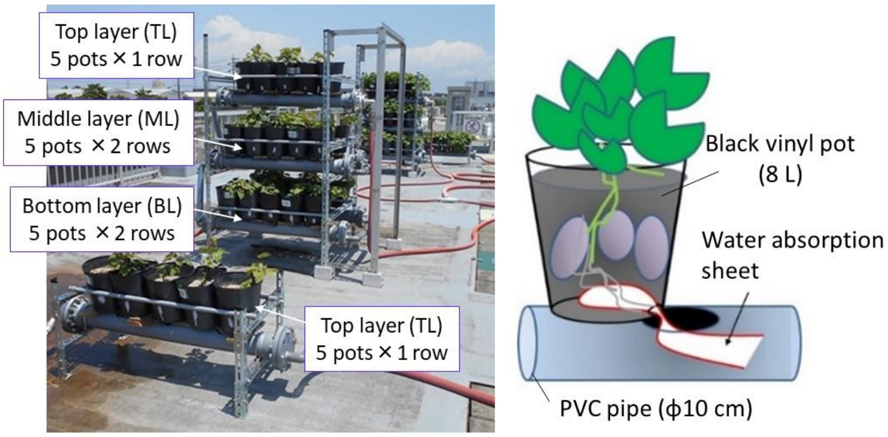

Figure 2. The three-layer cultivation system with rhizosphere irrigation.

To equalize the number of samples in each layer, a single layer with 5 pots was also used as the top layer, for a total of 30 pots in a set. For the comparison of the effect of PS water and FS water on fertilization, 2 sets (60 pots) each were used to compare the yields of tuberous roots and leaves and stems. For commercial liquid fertilizer cultivation, 3 sets (90 pots) were used to compare yields.

2.3. Winter Cultivation Using Greenhouse Supplied with Sewage Treatment Water

After harvesting sweet potatoes in November, vines of SK and BH were cut to about 50 cm and replanted in December as new seedlings for winter cultivation. Figure 3 shows the overwintering cultivation system. For four months from December to March, two sets of three-layer cultivation systems were covered with plastic film hoods, continuously supplied with treated sewage water (FS water) and fertilized and heated with rhizosphere irrigation. Using a data logger (TR-74 Ui, T & D, Tokyo, Japan), the temperature inside and outside the greenhouse and the temperature of treated sewage water in winter were measured to analyze the heating effect. The plastic hood was removed in April and cultivation continued until late July. The cultivation period over winter was 233 days.

Figure 3. Three-layer cultivation greenhouse with rhizosphere irrigation supplying treated sewage water.

In this report, cultivation during the normal season, from June to November, is referred to as “summer cultivation”, while cultivation from December to the following July is referred to as “winter cultivation”.

2.4. Solar Radiation Ratio in Three-Layer Cultivation

The solar radiation ratio (SR) of each layer was calculated using the illuminance of each layer reported in the previous paper [16]. In PS and FS water supply tests, since the distance between the two three-layer sets was great, SR was calculated as 100% for the top layer, 85% for the middle layer and 73% for the bottom layer. On the other hand, when commercial liquid fertilizers were used, the average solar radiation was 74% in the middle layer and 54% in the lower layer due to the narrow spacing between the sets of three layers.

2.5. Photosynthetic Efficiency in Three-Layer Cultivation

The cumulative value of solar radiation for the entire 160 d cultivation period from June to November was set at 2480 MJ m^{-2} [16]. Total solar radiation for the FS and PS irrigation systems was calculated as 2180 MJ m^{-2} in the middle and 1810 MJ m^{-2} in the lower layers by multiplying the SR in each layer by 2480 MJ m^{-2}. Similarly, the LF water supply was 1835 MJ m^{-2} for the middle layer and 1339 MJ m^{-2} for the lower layer.

On the other hand, the cumulative solar radiation during the 233 d cultivation period from December to July was 3416 MJ m^{-2} for the top layer, 2904 MJ m^{-2} for the middle layer and 2494 MJ m^{-2} for the lower layer.

Fresh and dry weights of harvested tuberous roots, leaves and stems were measured, and the heat value was calculated by multiplying the dry matter weight by 17 MJ kg^{-1} [36] to calculate the energy yield relative to the total amount of solar radiation in each layer.

2.6. Statical Analysis

Statistical analysis was performed using the statistical analysis tool in Microsoft Excel 2019. The mean and standard error of the opposing elements were obtained using each solar radiation rate (position of the shelf) as a conditional element was indicated. Analysis of variance (ANOVA) was also applied to the resulting data. The significance of the differences between the condition elements was determined using a t-test between the two elements assuming unequal variance, and groups with significant differences of $p < 0.05$ were indicated by different letters in the figures.

3. Results

3.1. Sweet Potato Production Using Sewage and Treated Sewage

The appearance of sweet potatoes grown under three-layer rhizosphere irrigation with commercial liquid fertilizer (LF water), raw sewage (PS water) and treated sewage (FS water) clearly differed according to the irrigation water species, as shown in Figure 4. When PS water was supplied, leaf growth was similar to that of LF water, but when FS water was supplied, leaf growth accelerated on a large scale. Figure 4 also shows the appearance of the harvested samples. It can be seen that the FS water supply caused the leaves to grow larger and more profusely, resulting in the production of a large amount of tuberous roots.

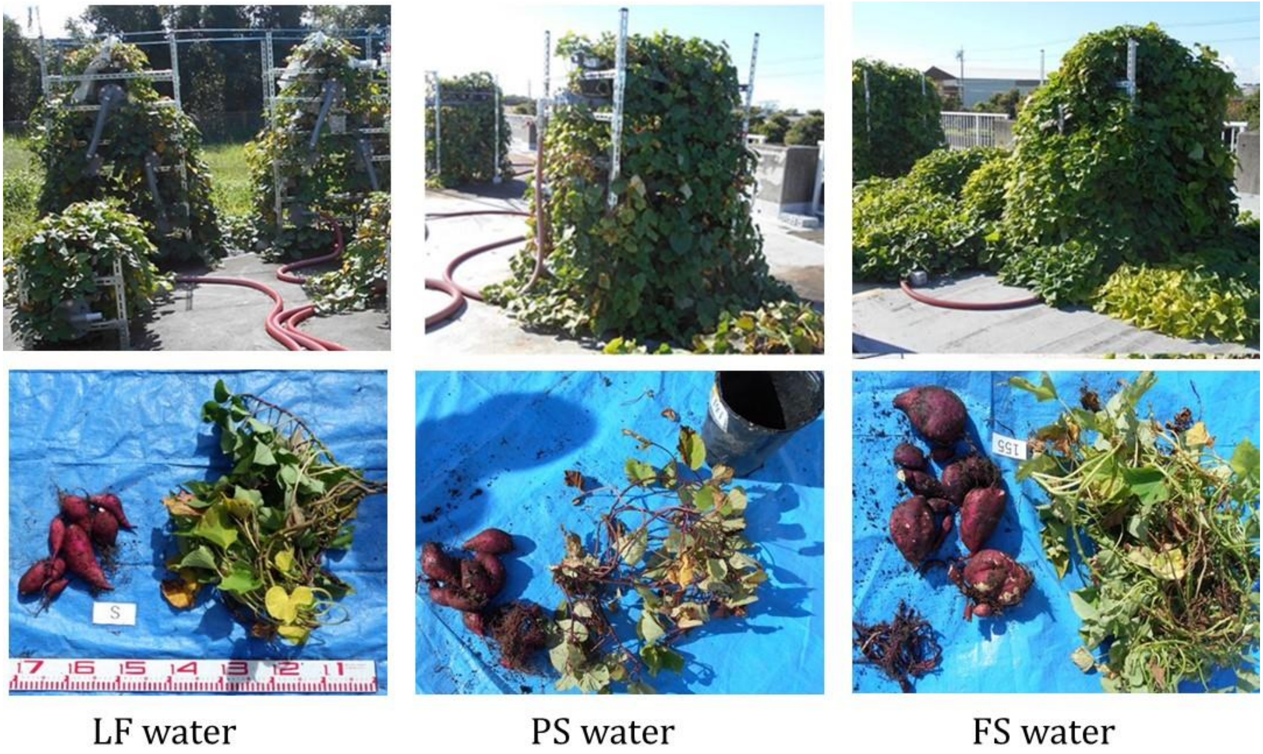

Figure 4. Growth of leaves and stems in three-layer rhizosphere irrigation cultivation using commercial liquid fertilizer (LF water), raw sewage (PS water) and treated sewage (FS water), and harvested tuberous roots, leaves and stems.

Figure 5 shows the fresh weight of tuberous roots, leaves and stems per pot harvested in the lower (BL), middle (ML) and upper (TL) layers in each water supply condition. When LF water without sewage was supplied, *Suikenkintoki* (SK) was 0.67 kg/pot (BL), 0.82 kg/pot (ML) and 0.89 kg/pot (TL), and *Benihalka* (BH) was 0.50 kg/pot (BL), 0.64 kg/pot (ML) and 0.86 kg/pot (TL).

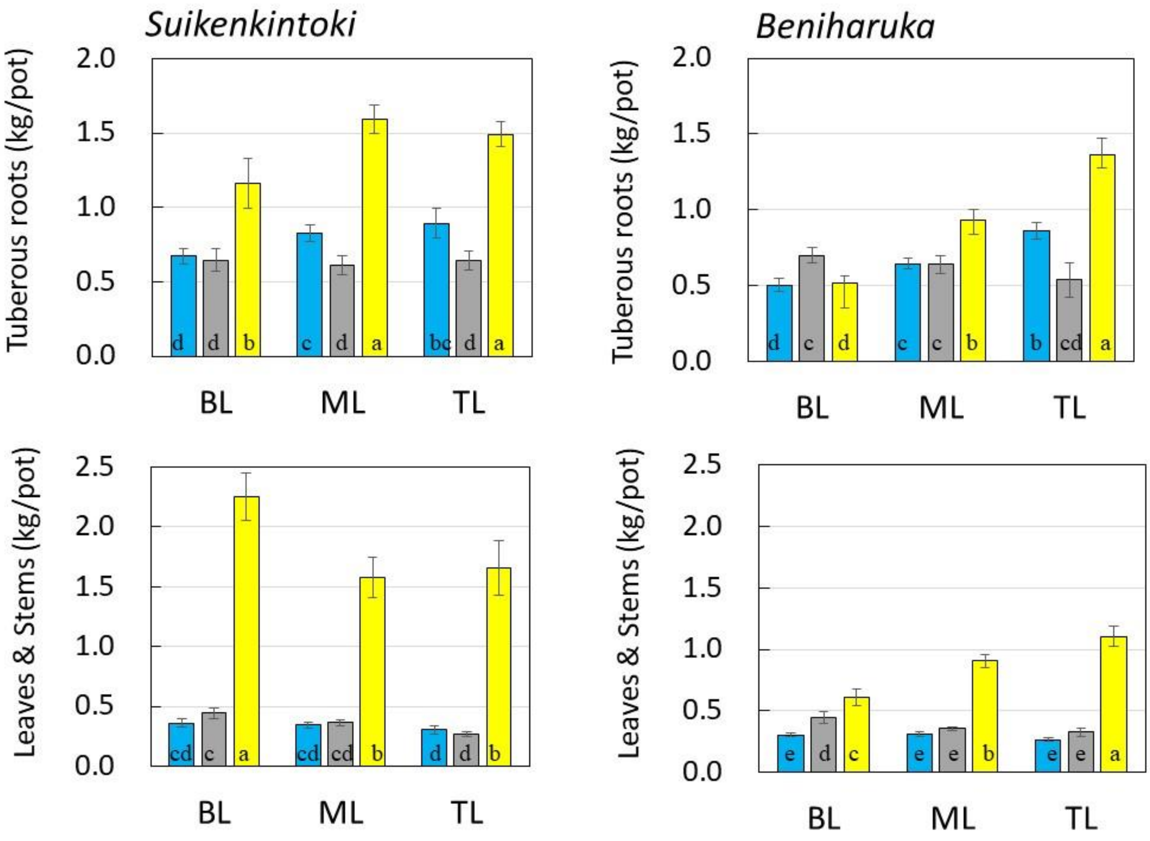

Figure 5. The fresh weight of tuberous roots, leaves and stems per pot harvested in bottom layer (BL), middle layer (ML) and top layer (TL). Symbols indicate the irrigation water : 🟦; LF water, ◼; PS water, 🟨; FS water. Data are means and error bars represent standard error of the mean. Different letters indicate statistically significant differences between cultivation layers ($p < 0.05$).

In contrast, the average yields of SK increased significantly to 1.16 kg/pot in the BL, 1.60 kg/pot in the ML and 1.49 kg/pot in the TL when irrigating with FS water. However, they were as low as 0.64 kg/pot in the BL, 0.61 kg/pot in the ML and 0.64 kg/pot in the TL with a PS water supply.

Similarly, the yields of BH were 0.52 kg/pot (BL), 0.93 kg/pot (ML) and 1.36 kg/pot (TL) with the FS water supply, while they were 0.70 kg/pot (BL), 0.64 kg/pot (ML) and 0.54 kg/pot (TL) with PS water irrigation.

Therefore, in the three-layer yield, both varieties produced significantly more tuberous roots when FS water was supplied, but the yields with a PS water supply were comparable or lower compared to the LF water supply.

On the other hand, the fresh weight of leaves and stems was significantly increased when FS water was supplied, especially in SK, and they grew about five times as much as PS and LF water. The upper and middle layers of BH also grew about three times as many leaves as those grown with PS and LF water. These results suggest that the supply of FS water led to a significant increase in leaves and stems, which in turn led to an increase in the yield of tuberous roots.

The total dry-matter weight per pot (the sum of tuberous roots, leaves, and stems) and the dry-weight ratio of tuberous roots (TR) to leaves and stems (LS) were compared for each layer, as shown in Figure 6. The three-layer average dry-matter weight for SK with an LF water supply was 630 g/pot, which was 2.3 times that with an LF water (271 g/pot). Similarly, the BH increased by 1.6 times over that with an LF supply (230 g/pot), reaching 380 g/pot with an FS supply.

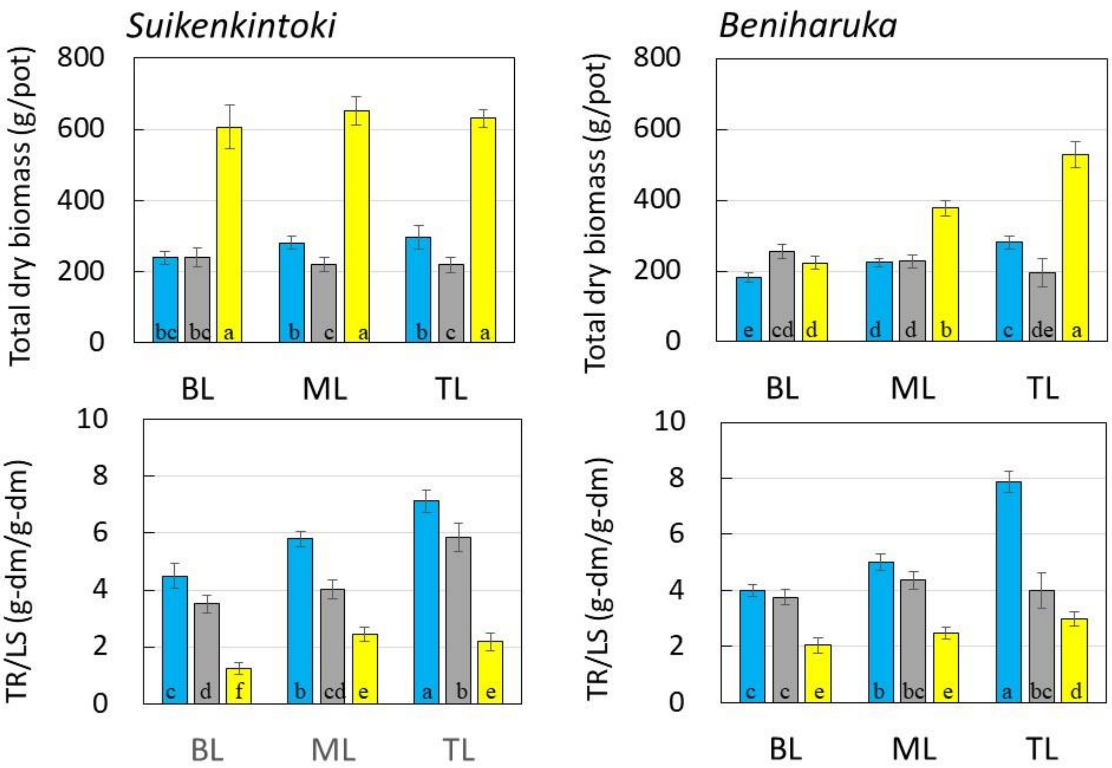

Figure 6. Total dry biomass weight (tuberous roots, leaves and stems), and the weight ratio of tuberous roots (TR) to leaves and stems (LS) per pot harvested in bottom layer (BL), middle layer (ML) and top layer (TL). Symbols indicate the irrigation water: 🟦; LF water, ■; PS water, 🟨; FS water. Data are means and error bars represent standard error of the mean. Different letters indicate statistically significant differences between cultivation layers ($p < 0.05$).

On the other hand, the average dry weight ratio of tuberous roots to leaves and stems (TR/LS) was 5.8 for SK and 5.6 for BH with an LF water supply; however, this ratio was significantly reduced to 1.9 for SK and 2.2 for BH with an FS water supply. Therefore, it can be seen that the FS supply accelerated the growth of leaves and stems more than the accumulation of tuberous roots.

Figure 7 shows the fine roots growing into the PVC pipe under each irrigation condition. When LF water was supplied, white fine roots grew abundantly at the bottom, but when PS water was supplied, fine roots propagated at the top and did not extend to the bottom. In other words, PS water had an excessively high BOD, which suggests that microbial growth caused a lack of DO in the water and that roots were growing on the water surface in the pipe.

LF water PS water FS water

Figure 7. In rhizosphere irrigation cultivation, the elongation of fine roots into PVC pipes varied greatly depending on the water supply of liquid fertilizer (LF water), raw sewage (PS water) and treated sewage (FS water).

On the other hand, FS water treated to reduce BOD below 15 ppm was considered to have fine roots growing into the bottom water because DO was maintained. In addition, when FS water was supplied, the brown coating was formed on the surface of the fine roots, suggesting that the microbial membrane attached to the roots increased the efficiency of nutrient absorption from treated sewage.

3.2. Winter Cultivation Supplied with Sewage Treatment Water

Based on the above results, treated sewage was selected as the irrigation for winter cultivation. Figure 8 shows the daily average and minimum temperatures for outside and in the greenhouse (In GH), and for root zone irrigation water (FS water) from December to January. The average temperature outside was always below 15 °C, and there were many days when the minimum temperature was below 5 °C or even close to 0 °C.

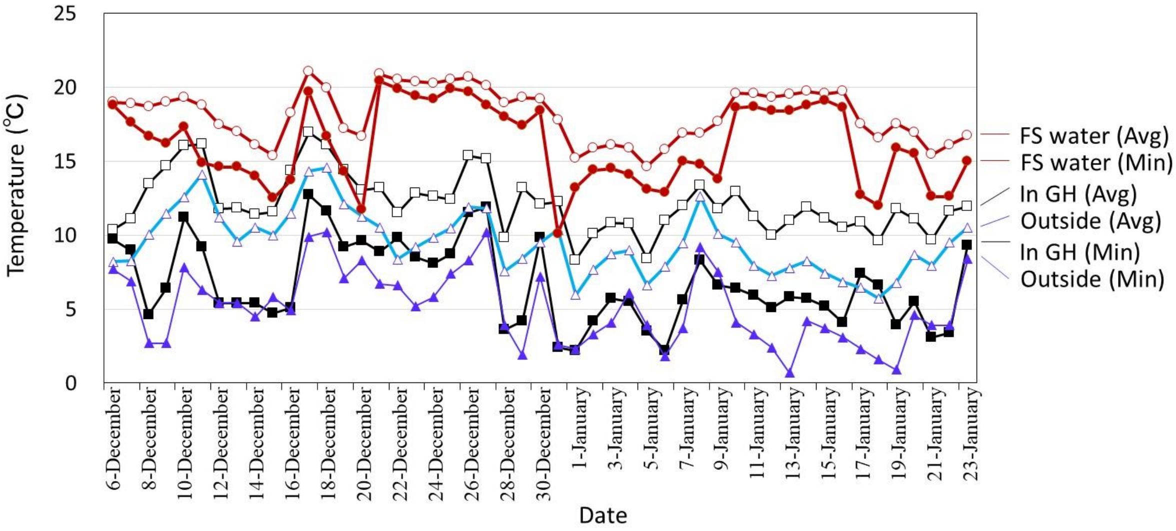

Figure 8. Daily average (Avg) and minimum (Min) temperatures for outside and in the greenhouse (In GH), and for root zone irrigation water (FS water) during winter cultivation period from December to January.

In contrast, the FS water maintained an average temperature in the range of from 15 °C to 20 °C and a minimum temperature always above 10 °C which kept the greenhouse temperature from 3 °C to 5 °C higher than outside. Although the temperature in the greenhouse in winter was not enough to encourage vigorous growth, it was effective in preventing the sweet potato crop from dying due to cold injury and drying, and maintained its growth through the winter season. In April, the greenhouse was removed and cultivation continued until the end of July.

Figure 9 shows the yields of tuberous roots and leaves and stems in winter cultivation. The tuberous roots of TL were 0.99 kg/pot in SK and 1.04 kg/pot in BH, which were higher than that of SK using LF water in summer cultivation in Figure 5.

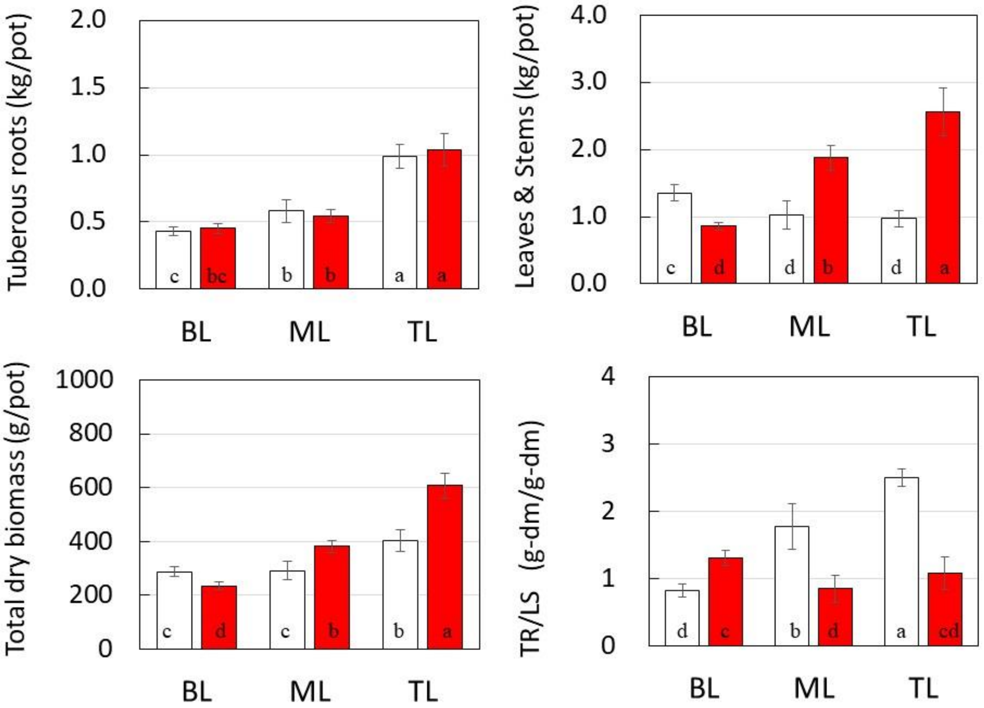

Figure 9. The fresh weight of tuberous roots, leaves and stems, the total dry biomass weight and the dry weight ratio of tuberous roots (TR) to leaves and stems (LS) per pot harvested in bottom layer (BL), middle layer (ML) and top layer (TL). Symbols: □, SK; ■, BH. Data are means and error bars represent standard error of the mean. Different letters indicate statistically significant differences between cultivation layers ($p < 0.05$).

On the other hand, in winter cultivation, leaves and stems increased to 1.35 kg/pot at BL for SK and 2.57 at TL for BH. As a result, the dry weight ratios of TR/LS at TL were 2.5 for SK and 1.1 for BH. These values were even lower than SK (Figure 6), which was the lowest weight ratio in summer cultivation, indicating excessive leaf growth.

These results indicated that it is possible to maintain sweet potato growth in the greenhouse by continuously supplying treated sewage in winter. However, it was found that not only FS water gave priority to the growth of stems and leaves, but low solar radiation intensity in winter cultivation also promoted the growth of leaves and stems and reduced the weight ratio of tuberous roots [16].

3.3. *Photosynthetic Efficiency in Summer and Winter Cultivations*

The effects of the treated sewage water on increasing the production of sweet potato biomass are summarized in Table 1. The upper row of the table shows the fresh weight of tuberous roots and leaves and stems, and the lower row shows the dry weight.

Table 1. Productivity and energy yield of summer and winter cultivations supplied with sewage treatment water.

Cultivation period		**Summer Cultivation June–November (160 d)**				**Winter Cultivation December–July (233 d)**				**Total (393 d)**	
		Tuberous Roots		**Leaves and Stems**		**Tuberous Roots**		**Leaves and Stems**		**Total Biomass**	
Layer	Fresh weight	SK	BH	SK	BH	SK	BH	SK	BH	SK	BH
TL	g-fm/pot	1493	1364	1656	1106	989	1037	971	2565	5110	6072
ML	g-fm/pot	1595	930	1578	905	581	543	1027	1873	4782	4252
BL	g-fm/pot	1162	517	2250	608	433	454	1352	859	5197	2438
Total yield *	kg-fm/25 pots	35.0	21.3	46.6	20.7	15.1	15.2	28.7	40.1	125	97
Productivity **	kg-fm/m^2	19.5	11.8	25.9	11.5	8.4	8.4	15.9	22.3	70	54
Layer	Dry weight	SK	BH	SK	BH	SK	BH	SK	BH	SK	BH
TL	g-dm/pot	433	396	199	133	287	301	117	308	1035	1137
ML	g-dm/pot	463	270	189	109	169	158	123	225	944	761
BL	g-dm/pot	337	150	270	73	125	132	162	103	895	458
Total yield *	kg-dm/25 pots	10.2	6.2	5.6	2.5	4.4	4.4	3.4	4.8	23.6	17.9
Energy yield ***	MJ-dm/MJ-solar	3.9%	2.4%	2.1%	0.9%	1.2%	1.2%	1.0%	1.3%	3.8%	2.9%

Total yield * = mean yield of TL × 5 pots + mean yield of ML × 10 pots + mean yield of BL × 10 pots. Productivity ** = total yield/1.8 m^2. Energy yield *** = dry biomass weight × 17 MJ/kg ÷ cumulative solar radiation during the growing period.

The productivity calculated based on the installed area of the three-layer cultivation system was 19.5 kg m^{-2} for SK and 11.5 kg m^{-2} for BH in summer cultivation, and 8.4 kg m^{-2} for both in winter cultivation. As a result, the yields of SK and BH were 27.9 kg m^{-2} and 20.2 kg m^{-2}, respectively, during the sum of 13 months of summer and winter cultivation. The productivity per 12 months was 10.7 and 7.8 times higher, respectively, than the national average of 2.4 kg m^{-2} [6] for open-field cultivation without winter cultivation.

The total dry biomass and energy production as the total dry weight of tuberous roots, leaves and stems produced over a 13-month-period in the three-layer cultivation arrayed with 25 pots was 23.6 kg-dm (223 MJ m^{-2}) for SK and 17.9 kg-dm (169 MJ m^{-2}) for BH.

The energy yield per 5896 MJ m^{-2} (sum of 2480 MJ for summer and 3416 MJ for winter cultivations) for 13 months was 3.8% for SK and 2.9% for BH, when the amount of solar radiation irradiated to the leaves extended outside the framework of the three-layer shelf was ignored.

Conventional sweet potato production yields leaves and stems from 2 to 3 kg m^{-2} per 2.4 kg m^{-2} of tuberous roots, with an estimated total dry weight of 1.0 kg m^{-2} (17 MJ m^{-2}) and a photosynthetic yield of 0.7% (=17 MJ/2480 MJ). However, since the normal cultivation does not capture solar energy during the 6–7 months of winter, the actual total energy yield at an average annual solar radiation of 5000 MJ m^{-2} in Japan is only about 0.34%.

Therefore, it can be concluded that the photosynthetic efficiency of the biomass production of sweet potatoes can be increased by more than 10 times by supplying treated sewage water even in winter and growing sweet potatoes in three layers throughout the year.

4. Discussion

Numerous studies and methods have been reported on the use of sewage and treated water as liquid fertilizer, but none has significantly affected biomass production as reported here. When sewage treatment water was supplied as rhizosphere irrigation of sweet potatoes, the yield of tuberous roots was found to increase significantly, with a marked increase in leaves and stems. The supply of treated sewage also made it possible to grow sweet potatoes during the winter season, yielding a fresh weight of SK of 27.9 kg

m^{-2} after a total of 13 months of cultivation. The annual productivity of tuberous roots was calculated to be 25.3 kg m^{-2} yr^{-1}, the total biomass energy yield for the annual solar radiation was 3.8% and energy productivity was 223 MJ m^{-2} yr^{-1}, demonstrating that the productivity of sweet potatoes could be increased by more than 10 times that of conventional field cultivation. These achievements are certain to provide new and powerful effective solutions to the problems of global warming and food shortages caused by population growth.

Since it has been considered essential that the production of biomass resources to replace fossil fuels does not compete with food production, research has focused on agricultural waste and woody biomass [37]. Lal estimated global annual agricultural biomass production at 3758 × 10^9 kg yr^{-1} (4.6 × 10^{13} MJ yr^{-1}) [38]. On the other hand, Sarkar et al. studied the amount of waste generated by major grain production and estimated that the sum of wheat straw, rice straw, corn stopover and sugarcane bagasse was 1394 × 10^9 kg yr^{-1} worldwide [39]. Assuming a moisture content of 10% and a calorific value of 15 MJ kg^{-1} for these wastes, the total calorific value is estimated to be 2.1 × 10^{13} MJ yr^{-1}. Thus, about half of agricultural biomass is available as a potential energy resource.

Meanwhile, global fossil fuel consumption reached 4.9 × 10^{14} MJ in 2021 and is still growing every year [40]. Therefore, it should be understood that even if all agricultural waste is utilized globally, the potential reduction of fossil fuels is only 4%, and in reality, the reduction of greenhouse gases from waste biomass is hardly expected.

Woody resources, which take decades to grow, are similarly unlikely to reduce greenhouse gases. In Japan, since the efficiency of woody biomass power generation is low, ranging from 25% to 30% [13], CO_2 emissions from 1 kWh of power generation will increase by 140% to 170% compared to maintaining coal power generation at an efficiency of 43% [12]. On the other hand, the conversion of coal to woody biomass does not change the growth rate of domestic forests [11], and the amount of CO_2 that can be recovered does not change at all, so it is inevitable that extra CO_2 emitted by woody fuels will accumulate in the atmosphere every year.

Thus, with current agricultural production and woody biomass resources, it is extremely difficult to reduce greenhouse gases, and the efficiency of plant biomass production must be greatly increased. Schwerz et al. investigated the production efficiency of woody resources and reported that the maximum production efficiency of woody biomass was 70~100 t ha^{-1} yr^{-1}, which was obtained by growing eucalyptus at a reduced spacing density [41]. Assuming a moisture content of 50% of the growing wood and a calorific value of 20 MJ kg-dm^{-1}, the maximum annual production of woody biomass through the cultivation of eucalyptus is estimated to be 70~100 MJ m^{-2} yr^{-1}. On the other hand, the maximum biomass production of sweet potatoes per unit area mentioned above was more than twice that of eucalyptus. Therefore, it is clear that sweet potatoes can absorb more than twice as much CO_2 from the atmosphere than eucalyptus.

In addition, many studies have been reported on the mass production of non-edible giant herbaceous plants that do not compete with food production. *Miscanthus* was suitable for mass production in the United States and Europe, with a maximum annual yield of 4.4 kg-dm m^{-2} yr^{-1} and 75 MJ m^{-2} yr^{-1} [42]. In Japan, a productivity of 3.9 kg-dm m^{-2} yr^{-1} and 66 MJ m^{-2} yr^{-1} was achieved by optimizing the cultivation conditions of *Erianthus* [43]. Napier grass is suitable for mass production in tropical regions [44], with a maximum production reported in Thailand of 58 t-dm ha^{-1} and 99 MJ m^{-2} yr^{-1} [45]. Thus, sweet potato productivity is also more than double the maximum yield of all reported giant herbaceous plants.

The biomass resources produced can be converted into methane through anaerobic digestion and fed into a cogeneration system that uses fuel cells to provide electricity and hot water, increasing energy efficiency to 90% [46]. However, because eucalyptus, a woody biomass plant, contains a lot of lignin and lignocellulose [47], the conversion rate to methane is very low and is limited to thermal power and combustion applications, which are less energy efficient.

Similarly, giant grasses, such as napier grass, have low anaerobic digestibility due to their high content of lignocellulose [48]. Experimental reports using napier grass mixed with livestock manure for methane production suggest that the methane yield from solid matter of napier grass ranges from 40% to 50% [49,50].

On the other hand, it has been reported that most of the biomass solids of sweet potatoes, with edible stems and tuberous roots, could be converted to methane in a short time using anaerobic digestion reaction mixed with sewage sludge [51].

In tropical regions, bagasse, after squeezing sugar solution from sugarcane, can be used as a biomass resource, so mass cultivation is being considered [52]. In Brazil, sugarcane productivity was reported to have reached 79 MJ m^{-2} yr^{-1} [53] in conventional farming and 98 kg-dm m^{-2} yr^{-1} (170 MJ m^{-2} yr^{-1}) in cultivation experiments [54]. However, with annual solar radiation in Brazil of 7500~8400 MJ m^{-2} yr^{-1} [55], 1.5 to 1.7 times that of Japan, estimates of photosynthetic efficiency are low, ranging from 2.0% to 2.2%, and both productivity and photosynthetic yield were significantly lower than the sweet potato results mentioned above.

Thus, the sweet potato production results presented here were significantly higher yields than all biomass production results reported in the past. These results suggest that the mass production of sweet potatoes would make it possible to replace all fossil fuels. Japan relied on fossil fuels for 15.6 TJ, or 84.8% of its annual energy consumption of 18 million TJ in 2020 [12]. The authors predicts that in the future, energy demand will decrease to 12 million TJ due to the development of an energy-saving society, including a significant increase in the rate of cogeneration by biomethane, which eliminates waste heat loss from thermal power plants, and the spread of electric vehicles, which are more energy efficient than gasoline vehicles [12]. Assuming that half of that would come from solar, hydropower, wind, geothermal and other sources, the amount of sweet potato production needed to completely eliminate fossil fuels is estimated to be 6 million TJ in the future. As the production efficiency of sweet potato has increased to over 200 MJ m^{-2} yr^{-1}, the area required to produce 6 million TJ of energy crops is estimated to be 3 million ha. This is equivalent to 7.9% of Japan's total area of 37.8 million ha, and is quite feasible. On the other hand, it is understandable that a conventional production efficiency of 20 MJ m^{-2} yr^{-1} would require 79% of the country's land area, which is impossible.

As a result, it is expected to be possible to mass produce sweet potato biomass using treated sewage water and completely eliminate fossil fuels. However, the details of the fertilization effect of treated sewage are unknown and require further investigation.

The sewage treatment plant used in the experiment was a conventional standard process to reduce BOD by aeration treatment, and this growth-promoting effect is expected to be universally obtained in any municipal sewage treatment plant.

In addition, the residual concentrations of fertilizer components, such as N, P, K and Mg, in sewage and treated water were lower than those in commercial liquid fertilizers, as shown in Figure 1, and EC was also in a moderate range for plant cultivation [56–58]. It was also found that raw sewage (FS water) contained more NH_4-N derived from human waste, while biological treatment reduced NH_4-N and instead increased NO_3-N, which is optimal for plant growth.

It is known that the excessive application of NO_3-N fertilizer, even in open-field cultivation, gives priority to the growth of stems and leaves and suppresses the enlargement of tuberous roots [59,60]. Thus, the continuous supply of NO_3-N contained in sewage treatment water (FS water) may have promoted the growth of leaves and stems more than the production of tuberous roots.

Another possibility is the effects of microorganisms. Active microorganisms grown in the aeration tank remained in the FS water before disinfection. When these active microorganisms attached to the fine roots and formed a microbial membrane, it was suggested that inorganic ions concentrated by the microorganisms in the sewage effluent and components produced by the microorganisms had a growth-promoting effect on the sweet potato.

In general, soil microorganisms are known to enhance the fertilizer effect in open-field cultivation [61], but the effect of rhizosphere microorganisms in hydroponics is unknown. The results of this study suggest that microorganisms in treated sewage may have an effect on enhancing the absorption of liquid fertilizer components by fine roots, but further research is required.

In any case, the continued supply of treated sewage to the rhizosphere suggested that the fertilizer required for crop production can be significantly reduced. Further investigation into the effects of fertilizer application of treated sewage is expected to suppress excessive growth of sweet potato leaves and stems, elucidate the stressors that promote tuberous root enlargement and further enhance photosynthetic efficiency.

On the other hand, as a result of supplying treated sewage water capable of maintaining 15 °C in winter to the rhizosphere, overwintering cultivation was successful and the annual yield of sweet potatoes increased by approximately 1.5 times. However, because the conversion rate of solar energy in winter cultivation was half or less than that of the summer cultivation, it is necessary to develop low-cost methods to further optimize the winter cultivation environment. As a result, it is expected that the productivity of sweet potatoes can be further enhanced by investigating the effect of sewage fertilization and increasing the efficiency of solar energy use throughout the year.

5. Conclusions

It was found that supplying treated sewage water to the root zone of sweet potatoes dramatically increased their productivity. As a result, the mass production of sweet potatoes has raised the possibility of eliminating all fossil fuels and reducing Japan's greenhouse gas emissions to virtually zero.

To produce such a large quantity of sweet potatoes requires a large amount of fertilizer, but it was found that supplying treated sewage as the fertilizer to the rhizosphere has an extremely high growth-promoting effect. It was also found that treated sewage water was effective as a heat source to continue winter cultivation.

The effect of sewage treatment water on fertilization needs further investigation. Finding fertilization conditions that limit excessive growth of stems and leaves and prioritize the enlargement of tuberous roots is expected to further improve productivity.

With a population of more than 8 billion that is still growing, humans continue to destroy forests to increase grain production. In addition, the consumption of fossil fuels continues to increase every year, increasing the number and scale of natural disasters caused by global warming [62]. To solve this problem, we proved that we can produce 10 times more biomass resources than conventional farming methods without increasing the farmland area. To replace all fossil fuels and stop global warming, methods for the mass production of biomass resources need to be further improved.

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Abbreviations

Avg, average; BH, *Beniharuka*; BL, bottom layer; BOD, biochemical oxygen demand; DO; dissolved oxygen; FS, final settling tank after aeration treatment; GH, greenhouse; LF, liquid fertilizer; LS, leaves and stems; Min, minimum; ML, middle layer; NH_4-N, ammonia nitrogen; NO_3-N, nitrate nitrogen; PS, primary settling tank; PVC, polyvinyl chloride; SK, *Suikenkintoki*; SR, solar radiation ratio; SS, suspended solid; TL, top layer; TR, tuberous roots; dm, dry matter; fm, fresh matter.

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