Production Efficiency of Animal-Feed Obtained From Food Waste in Japan

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1 **Production efficiency of animal-feed obtained from food waste in Japan**

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Abstract

Converting food waste into animal-feed is highly useful for tackling the problem of food waste, which is particularly severe in developed countries. This study quantified inefficiencies in converting food waste into animal-feed and identified their causes through a data envelopment analysis (DEA) of the monthly input–output data of two producers of animal-feed obtained from food waste in Japan. Our empirical analysis revealed that the producers of animal-feed obtained from food waste (especially those treating food waste from retail and service industries) demonstrated inefficiencies in production technology and scale; moreover, expanding the production scale and improving the quality of food waste could enhance production efficiency. Based on the empirical results, specific policy implications were provided for the widespread use of animal-feed obtained from food waste in Japan and elsewhere, globally. Furthermore, it was found that the COVID-19 pandemic contributed to a severe reduction in the production efficiency of animal-feed producers treating food waste obtained from retail and service industries.

Keywords: *production efficiency; data envelopment analysis; food waste; animal-feed; COVID-19*

29 **Abbreviations**

30 CAA: Consumer Affairs Agency; COVID-19: Coronavirus disease 2019; CV: Coefficient of
31 variation; CRS: Constant returns to scale; DEA: Data envelopment analysis; DMU: Decision-
32 making unit; EU: European Union; FAO: Food and Agriculture Organization of the United
33 Nations; GHG: Greenhouse gas; IRS: Increasing returns to scale; LCA: Life cycle assessment;
34 LCC; Life cycle cost; MAFF: Ministry of Agriculture, Forestry, and Fisheries; ME: Ministry
35 of the Environment; NIRS: Non-increasing returns to scale; PTE: Pure technical efficiency;
36 QFW: Quality of food waste; RTS: Returns to scale; SBM: Slacks based measure; SDG:
37 Sustainable development goal; SE: Scale efficiency; SP: Slack proportion; TDN: Total
38 digestible nutrient; TE: Technical efficiency; UK: United Kingdom; UNEP: United nations
39 environment program; US: United States; VRS: Variable returns to scale; WFP: World Food
40 Program

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO) (2018), ~800 million people worldwide suffered from hunger and malnutrition in 2017, and ~150 million children under the age of five suffered from stunting. Conversely, global food waste is estimated to be ~1.3 billion tons per year, which is roughly one-third of global production (FAO, 2011). Food is progressively disposed of in the process from production to consumption (i.e., the food supply chain). In developing countries, food waste at the consumption stage is considerably low, whereas most food waste in developed countries occurs at the consumption stage (Ministry of Agriculture, Forestry, and Fisheries (MAFF); and Ministry of the Environment (ME), 2013). In addition, this imbalance in food waste between developed and developing countries is also known to cause global energy and environmental waste. In expanding global supply chains, additional amounts of food with high water content is produced in places where it is not directly consumed, and is transported and disposed of over long distances, resulting in wasteful use of fossil fuels and increased greenhouse gas (GHG) emissions (MAFF, 2020a). To address these issues, the sustainable development goals (SDGs) established at the 2015 United Nations Summit called for "zero hunger (Target 2)," "good health and well-being (Target 3)," "affordable and clean energy (Target 7)," "responsible consumption and production (Target 12)," and "climate action (Target 13)" (United Nations Environment Programme (UNEP), 2015). In particular, the calls to "halve per capita global food waste by 2030

at retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses (Target 12.3)" and to "substantially reduce waste generation by 2030 through prevention, reduction, recycling, and reuse (Target 12.5)," were directly related to food waste.

Food waste is considerably severe in Japan, which is a developed country. In 2016, food waste in Japan amounted to ~27.59 million tons (business waste: 19.70 million tons; household waste: 7.89 million tons), being one of the worst, globally (MAFF, 2020a). In particular, 6.43 million tons (23%) of food waste (hereafter, edible food waste) was discarded despite being edible, which is 1.6 times the amount of food aid provided by the World Food Program (WFP) (~3.9 million tons) (Consumer Affairs Agency (CAA), 2020; WFP, 2017). Furthermore, the disposal of food waste incurs huge social costs (~2 trillion yen per year), and the shortage of landfill sites is also a challenge (CAA, 2020; Liu et al., 2016). The Japanese government aims to halve edible food waste in both business and household waste by 2030 (CAA, 2020).

The reduction of business food waste (including food manufacturing, wholesaling, retailing, and service industries) in Japan is mainly promoted through the following four methods: conversion to animal-feed, conversion to fertilizers, utilization as biogas through

methane fermentation (e.g., biogas power generation), and utilization as oil and fat products (e.g., production of biodiesel, paints, and inks) (MAFF and ME, 2013). In particular, the use of business food waste as animal-feed is the most popular method of recycling food waste in Japan. In fact, ~74% (9.13 million tons) of the total business food waste recycled in 2017 (12.3 million tons) was used as animal-feed (MAFF, 2020b). Animal-feed produced from food waste (e.g., food dregs and expired food items in the process of food production, cooking, and selling) is called "eco-feed" in Japan. The production of eco-feed can not only contribute to the reduction of food waste, but can also help overcome the low rate of food self-sufficiency in Japan (Liu et al., 2016; Sugiura et al., 2009). Japan is extremely dependent on food imports, with a calorie-based food self-sufficiency rate of 37% in 2018, which is one of the lowest among developed countries (CAA, 2020). In particular, in 2019, the feed self-sufficiency rate in Japan was ~25%, and the majority (~88%) of the concentrated feed, such as soybean and corn, used by livestock farmers were imported (MAFF, 2020b). The Japanese government has set a feed self-sufficiency target of 34% for 2030 to prevent livestock farmers from over-reliance on imported feed (MAFF, 2020b). Moreover, MAFF (2020b) reported that the use of animal-feed obtained from food waste, which is cheaper than imported feed, could help reduce the feeding cost and improve the feeding productivity for livestock farmers. Therefore, the Japanese government prioritizes reducing business food waste by converting it into animal-feed and supports its production and dissemination by providing subsidies to related businesses (MAFF, 2020b). In

2019, the production of animal-feed from food waste in Japan was ~1.19 million total digestible nutrient (TDN) tons (~6% of total concentrate feed), which is increasing annually (MAFF, 2020b).

The use of business food waste as animal-feed has many advantages as mentioned above; however, its widespread use has challenges such as lack of safety, uneven nutritional composition, and high production cost (Sugiura et al., 2009). In general, food waste is prone to decay during collection, transportation, and storage due to its high-water content; moreover, the quality of the animal-feed produced from food waste is susceptible to deterioration (Sugiura et al., 2009). In addition, business food waste (especially from food retailing and service) is not always available in constant quantities and the nutritional content is not always homogeneous (Sugiura et al., 2009). These aspects are particularly influential in the feed-conversion process of business food waste obtained from food retailing and service. In fact, approximately 80% and 57% of the business food waste obtained from food manufacturing and wholesaling generated in 2017 were recycled into animal-feed and fertilizer, respectively. Conversely, approximately 39% and 20% of business food waste obtained from food retailing and service, respectively, were recycled (MAFF, 2020b). Additionally, the use of food waste as animal-feed is not yet globally widespread due to the risk of diseases such as foot-and-mouth disease and African swine fever (Salemdeeb et al., 2017; zu Ermgassen et al., 2016). In the European Union

(EU), the use of food waste as animal-feed was banned after the spread of foot-and-mouth disease in 2002 (Salemdeeb et al., 2017; zu Ermgassen et al., 2016). In contrast, in East Asian countries such as Japan and Korea, the heat treatment of collected food waste is mandatory while converting food waste to prevent the infection of livestock with diseases (Salemdeeb et al., 2017; Sugiura et al., 2009; zu Ermgassen et al., 2016).

Quantifying the inefficiencies in the process of converting food waste into animal-feed and identifying their causes is critical toward enhancing the efficiency of producing animal-feed from food waste and in promoting the method in Japan as well as globally. Herein, a data envelopment analysis (DEA) was undertaken considering the monthly input–output data of two producers of animal-feed obtained from food waste in Japan to analyze the monthly production efficiency in converting food waste into animal-feed. The DEA is a nonparametric method that identifies the shape of the production frontier based on observed input–output combinations; moreover, it helps measure the efficiency score of each decision making unit (DMU) based on the relative distance between the identified frontier and the DMUs (Banker et al., 1984; Charnes et al., 1974). Specifically, we first collected monthly input and output data from January 2017 to July 2020 from two producers of dry animal-feed obtained from food waste in Japan: "Producer-A" (treating food waste from manufacturing and wholesaling); and "Producer-B" (treating food waste from retail and service). Thereafter, by applying the slacks-based measure

(SBM) model proposed by Tone (2001) in the DEA framework considering each of the two cross-sectional data, three relative production efficiency scores (i.e., technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE)) were estimated for each company, monthly. In addition, we estimated the slack proportion (SP) for each of the three inputs (electricity, heavy oil, and diesel fuel consumptions) in order to identify the causes of inefficiency considering the monthly production activities of each company. This study primarily aimed to discuss specific ways to improve the efficiency of converting food waste into animal-feed by quantifying the inefficiencies and identifying their causes. The empirical results of this study could contribute toward the widespread use of food waste as animal-feed, not only in Japan but also globally.

2. Literature review

A number of studies have discussed food waste issues in recent years using various approaches and covering various countries. Several studies provided surveys and reports on the amount of food waste and disposal methods in various countries based on statistical data and prevailing studies. Halloran et al. (2014) investigated food waste reduction efforts in Denmark and concluded that multi-stakeholder collaborations are crucial for arriving at sustainable solutions toward reducing food waste in Denmark. Parry et al. (2015) provided case studies for food loss and waste policy practices in Japan and the United Kingdom (UK). According to their

study, food waste in the food industry has decreased in Japan; however, food waste at the consumer stage has remained unchanged over recent years. Liu et al. (2016) analyzed the food waste trend in Japan during 1960–2012 and summarized the status of food waste in the Japanese food supply chain in 2011. They reported that there was almost no potential for further reduction in food waste from the food manufacturing industry, which has primarily been recycled through animal-feed and fertilizer; however, great potential exists in reducing food waste from other food industries, especially the food service industry. These existing studies show that food waste is a severe problem in many countries and that a potential exists for recycling huge quantities of food waste in each country.

The life cycle assessment (LCA) approach is often used to evaluate the environmental performance of food waste treatment methods. Lee et al. (2007) employed the LCA approach to estimate changes in the environmental impacts of food waste treatment systems (landfills, incineration, composting, and feed manufacturing) in Seoul during 1997–2005; their empirical analysis revealed that landfills primarily contributed to human toxicity and global warming. Kim and Kim (2010) evaluated feed manufacturing including dry feeding, wet feeding, composting, and landfilling for food waste disposal options considering lifecycle CO₂ emissions; their empirical results indicated that dry feeding had the lowest lifecycle CO₂ emissions per ton of food waste. Takata et al. (2012) employed the LCA and life cycle cost

(LCC) approaches to evaluate the environmental and economic efficiency of the five food recycling facilities (i.e., machine integrated compost, windrow compost, liquid feed, dry feed, and bio-gasification) in Japan; they found that dry feed facilities had low total GHG emissions due to a high substitution effect, and they had high running costs due to low revenues obtained from food collection fees. Moult et al. (2018) assessed eight food waste disposal options for UK retailers considering reduction in GHG emissions using the LCA approach; they concluded that, for all food types, landfills were the worst disposal option. These studies clearly showed that conversion of animal-feed from food waste was environmentally superior to other treatment methods.

Except for Japan and Korea, the conversion of food waste into animal-feed is hardly tackled in other countries due to safety issues (zu Ermgassen et al., 2016). However, several studies investigated the possibility of its widespread use in the EU, the United States (US), and other countries, focusing on its favorable environmental performance. Sugiura et al. (2009) surveyed and introduced the entire process from collection of food waste to its final production and sale as eco-feed in Japan; they also reported on specific preventive measures against bovine spongiform encephalopathy in the production of eco-feed in Japan. Cheng and Lo (2016) investigated the market demand, technical viability, feed quality, regulatory hurdles, and potential contribution to examine the feasibility of converting food waste into fish feed in Hong

193 Kong; the results showed that significant quantities of food waste could be recycled by
194 converting it into fish feed due to the enormous demand from feed factories in mainland China.
195 The conversion of food waste into animal-feed in Japan and Korea was reviewed by zu
196 Ermgassen et al. (2016) to quantify the potential of food waste for replacing conventional
197 animal-feed and reducing the environmental impact of meat production in EU. According to zu
198 Ermgassen et al. (2016), recycled animal-feed is attractive to the EU because of its low cost and
199 low environmental impact; however, additional efforts are needed to address consumer and
200 farmer concerns about food safety and disease control before it is widely adopted. Saleemdeen
201 et al. (2017) investigated the potential benefits of diverting food waste toward pig feed in the
202 UK; they employed the LCA approach to compare the environmental and health impacts of four
203 technologies for food waste processing (wet pig feed and dry pig feed in South Korea; and
204 anaerobic digestion and composting in UK). They concluded that the use of food waste as pig
205 feed could offer environmental and public health benefits in the UK with the support of policy
206 makers. Truong et al. (2019) conducted an extensive literature review focusing on the
207 conversion of food waste into animal-feed in the US food supply chain; according to their
208 survey, utilizing food waste as animal-feed (especially for chickens) in California could help
209 reduce food waste from landfills while providing nutrition to animals and subsequently humans.
210 Considering these studies, it is desirable to further promote the use of food waste as animal-

feed in various countries because it has excellent environmental and economic benefits;
although, safety is an issue.

In addition to safety concerns, the poor quality of the produced animal-feed is an issue that must be overcome. Therefore, several studies were conducted to improve the productivity of animal-feed obtained from food waste. Westendorf et al. (1998) compared pigs raised on cafeteria food waste with those raised on corn or soybean meal considering growth, meat quality, and dietary digestibility; the results indicated that food waste has nutritional value and could be useful in swine diets. Khounsaknalath et al. (2010) compared the growth performance and taste of beef cattle raised on eco-feed with that of beef cattle raised on normal feed; their results revealed that eco-feed had no negative effect on the animal growth and taste of beef. In Ruttanavut et al. (2011), Ruttanavut and Yamauchi (2012), and Takahashi et al. (2012), the growth performance of chickens and pigs raised on eco-feed was investigated to determine the optimal feeding level.

The aforementioned studies evaluated the environmental and economic performance of processing food waste into animal-feed, assessed the applicability of its introduction in various countries considering safety, and contributed toward helping enhance the quality of animal-feed. However, these studies provided no quantitative measurements of the

inefficiencies or the causes of such inefficiencies in the process of converting food waste into animal-feed. Kagawa et al. (2013) and Eguchi et al. (2015) employed the DEA to evaluate the efficiency of the production of biodiesel. In Kagawa et al. (2013), the DEA was applied to monthly input and output data of a plant producing biodiesel from waste cooking oil to evaluate the monthly production efficiency. They discovered a large gap in the monthly efficiency in the biodiesel production process considering the difference in the estimated production efficiency scores for each month. Additionally, they demonstrated that an improvement in production efficiency led to a reduction in the biodiesel production cost. Eguchi et al. (2015) developed the work done in Kagawa et al. (2013) to consider life cycle CO₂ emissions. Their empirical studies revealed that improvements in production efficiency not only helped reduce production costs but also lifecycle CO₂ emissions. Here, the DEA-based monthly production efficiency evaluation framework proposed by Kagawa et al. (2013) and Eguchi et al. (2015) were applied to develop a novel framework for evaluating monthly production efficiency and identifying the causes of inefficiency in food waste recycling plants.

This study has two novel aspects: (1) it is the first to focus on the gap in the monthly production efficiency in the process of converting food waste into animal-feed. Previous studies (Kim and Kim, 2010; Lee et al., 2007; Moult et al., 2018; Takata et al., 2012) compared other treatment methods and the environmental and economic efficiency of converting food waste

into animal-feed; however, no study investigated the efficiency gap considering the animal-feed conversion process itself; (2) it is the first to identify the causes of inefficiency in the process of converting food waste into animal-feed. Kagawa et al. (2013) and Eguchi et al. (2015) proposed frameworks to estimate the potential for reducing production costs and CO₂ emissions by improving the efficiency; however, the causes of inefficiencies were unidentified.

3. Methodology

3.1. Efficiency analysis considering the SBM model

The DEA is a mathematical approach used for evaluating relative efficiency among different DMUs. The DEA was originally proposed by Charnes et al. (1978); thereafter, it was used extensively in operations research, management, and economics (Emrouznejad and Yang, 2018; Mahmoudi et al., 2020; Sueyoshi et al., 2017; Zhou et al., 2018). This study employed the SBM model developed by Tone (2001) to measure the technical efficiency of animal-feed production. Following Tone (2001), the SBM DEA model could be formulated as follows:

$$\text{Minimize} \quad TE_n = \frac{1 - (1/J) \sum_{j=1}^J s_{jn}^x / x_{jn}}{1 - (1/K) \sum_{k=1}^K s_{kn}^y / y_{kn}} \quad (1)$$

$$\text{subject to} \quad \mathbf{x}_n = \mathbf{X}\boldsymbol{\lambda} + \mathbf{s}^x, \mathbf{y}_n = \mathbf{Y}\boldsymbol{\lambda} - \mathbf{s}^y, \boldsymbol{\lambda} \geq \mathbf{0}, \mathbf{s}^x \geq \mathbf{0}, \mathbf{s}^y \geq \mathbf{0} \quad (2)$$

where TE_n is the technical efficiency score of DMU n ; J represents the number of inputs; K represents the number of outputs; s_{jn}^x and s_{kn}^y denote slacks of the j^{th} input and k^{th} output for DMU n , respectively; x_{jn} and y_{kn} are the j^{th} input and k^{th} output for DMU n , respectively;

and $\mathbf{x}_n$ and $\mathbf{y}_n$ are the input and output vectors for DMU n , respectively. $\mathbf{X}$, $\mathbf{Y}$, $\boldsymbol{\lambda}$, $\mathbf{s}^x$, and $\mathbf{s}^y$ are the input matrix, output matrix, intensity weight vector, input slack vector, and output slack vector, respectively. $\boldsymbol{\lambda}$, $\mathbf{s}^x$, and $\mathbf{s}^y$ were endogenously determined by solving the above linear programming problem. TE_n ranged between 0 and 1 ($0 < TE_n \leq 1$); while $TE_n = 1$ indicated that DMU n was efficient. Conversely, a lower efficiency score indicated greater inefficiency. The fractional programming problem is based on the constant returns to scale (CRS) assumption; moreover, the problem can be extended into the variable returns to scale (VRS) model by adding the constraint $\sum_{n=1}^N \lambda_n = 1$ to Eq. (2), where N is the number of DMUs. By solving the VRS SBM model, we could obtain a pure technical efficiency score of DMU n (PTE_n).

According to Banker et al. (1984) and Shi et al. (2010), TE_n and PTE_n have the following relationship:

$$TE_n \leq PTE_n \quad (3)$$

In addition, the scale efficiency of DMU n (SE_n) could be calculated as follows:

$$SE_n = \frac{TE_n}{PTE_n} \quad (4)$$

SE_n also ranged between 0 and 1; moreover, a lower value of the scale efficiency indicated a more inefficient production scale. In other words, DMUs with a lower scale efficiency operate at a considerably small/large production scale; furthermore, they need to control the production

scale to improve scale efficiency. Eq. (4) could be rewritten as follows:

$$TE_n = PTE_n \times SE_n \quad (5)$$

Eq. (5) indicates that the technical efficiency could be decomposed into two terms: pure technical efficiency and scale efficiency. The overall technical efficiency of DMUs could be improved by improving the pure technical efficiency and scale efficiency (Shi et al., 2010).

Fukuyama (2001) and Shi et al. (2010) used an additional DEA model called the non-increasing returns to scale (NIRS) model to observe the properties of a DMU including CRS, increasing returns to scale (IRS), or decreasing returns to scale (DRS). The NIRS model is as follows:

$$\text{Minimize} \quad NTE_n = \frac{1 - (1/J) \sum_{j=1}^J s_{jn}^x / x_{jn}}{1 - (1/K) \sum_{k=1}^K s_{kn}^y / y_{kn}} \quad (6)$$

$$\text{subject to} \quad \mathbf{x}_n = \mathbf{X}\boldsymbol{\lambda} + \mathbf{s}^x, \mathbf{y}_n = \mathbf{Y}\boldsymbol{\lambda} - \mathbf{s}^y, \sum_{n=1}^N \lambda_n \leq 1, \boldsymbol{\lambda} \geq \mathbf{0}, \mathbf{s}^x \geq \mathbf{0}, \mathbf{s}^y \geq \mathbf{0} \quad (7)$$

where NTE_n is the NIRS technical efficiency of DMU n . Following Shi et al. (2010), this study defines a DMU's nature of returns to scale (RTS) as follows:

- (1) If $PTE_n > NTE_n = TE_n$, a DMU's nature of RTS is IRS. This implies that if the inputs were increased by t times, then the outputs would increase by $> t$ times. Therefore, the scale efficiency of such DMUs could be improved by expanding the production scale.
- (2) If $PTE_n = NTE_n > TE_n$, a DMU's nature of RTS is DRS. This implies that if the inputs

were increased by t times, then the outputs would increase by $< t$ times. Therefore, the scale efficiency of such DMUs could be improved by contracting the production scale.

(3) If $PTE_n = NTE_n = TE_n$, a DMU's nature of RTS is CRS. This implies that if the inputs were increased by t times, then the outputs would increase by t times. Therefore, the production scale of such DMUs is appropriate (i.e., $SE_n = 1$).

3.2. SBM model with fixed inputs

In some cases, there are some fixed inputs and a decision maker is not allowed/willing to reduce such inputs (Banker and Morey, 1986; Esmacili and Rostamy-Malkhalifeh, 2017; Takayabu, 2020). Here, food waste was considered as a fixed input, because collecting greater quantities of food waste and producing more animal-feed from food waste is desirable for a circular economy. In other words, animal-feed producers are considered to be unwilling to reduce the amount of food waste collected. Following Esmacili and Rostamy-Malkhalifeh (2017), a CRS SBM model with fixed inputs could be expressed as follows:

$$\text{Minimize} \quad TE_n = \frac{1 - (1/J) \sum_{j=1}^J s_{jn}^x / x_{jn}}{1 - (1/K) \sum_{k=1}^K s_{kn}^y / y_{kn}} \quad (8)$$

$$\begin{aligned} & \text{subject to} \\ & \mathbf{x}_n = \mathbf{X}\boldsymbol{\lambda} + \mathbf{s}^x, \\ & \mathbf{x}_n^{\text{fixed}} = \mathbf{X}^{\text{fixed}}\boldsymbol{\lambda} + \mathbf{s}^{\text{fixed}}, \\ & \mathbf{y}_n = \mathbf{Y}\boldsymbol{\lambda} - \mathbf{s}^y, \quad \boldsymbol{\lambda} \geq \mathbf{0}, \quad \mathbf{s}^x \geq \mathbf{0}, \quad \mathbf{s}^{\text{fixed}} \geq \mathbf{0}, \quad \mathbf{s}^y \geq \mathbf{0} \end{aligned} \quad (9)$$

where $\mathbf{x}_n^{\text{fixed}}$ denotes a fixed input vector for DMU n ; $\mathbf{X}^{\text{fixed}}$ denotes a fixed input matrix; and

$\mathbf{s}^{\text{fixed}}$ denotes a slack vector for a fixed input. Note that slacks for a fixed input are not considered in the objective function in Eq. (8).

For an empirical analysis, this study considered three inputs (electricity, heavy oil, and diesel oil consumption), one fixed input (collected food waste), and one output (animal-feed production) for 43 months (January 2017 to July 2020). Thus, the number of inputs is 3 ($J = 3$), the number of outputs is 1 ($K = 1$), and the number of DMUs is 43 ($N = 43$).¹

3.3. Slack proportion (SP)

Solving Eqs. (8) and (9), we could obtain a slack value for each input and output. The obtained slack values indicated a potential reduction (expansion) in the input (output); higher slack values indicated greater inefficiency. However, DMUs with a higher input and output tended to have higher slack values. Eguchi et al. (2021) and Nakaishi et al. (2021) normalized slack values by calculating the SP. Following Eguchi et al. (2021) and Nakaishi et al. (2021), SP was calculated as follows:

$$\mathbf{SP}_n^x = \frac{\mathbf{s}_n^x}{\mathbf{x}_n} \quad (10)$$

¹ Specifically, in our empirical study, we evaluated the monthly production efficiency of two animal-feed producers at different production frontiers. This is because the food waste collection channels and equipment used in the production process of these two producers varied (see Section 4).

$$\mathbf{SP}_n^y = \frac{\mathbf{s}^y}{\mathbf{y}_n} \quad (11)$$

where $\mathbf{SP}_n^x$ and $\mathbf{SP}_n^y$ denote the input and output SP vectors for DMU n , respectively. SP could be regarded as the technology improvement potential of the prevailing technology level of each input and output (Eguchi et al., 2021; Nakaishi et al., 2021). Note that the SP ranges from 0 to 1; moreover, a higher slack proportion value indicates greater inefficiency.

4. Data

Here, the monthly input (electricity, heavy oil, diesel oil, and food waste consumption) and output (animal-feed production) data from January 2017 to July 2020 collected from two manufacturers (i.e., Producer-A and Producer-B) producing animal-feed from food waste in Japan were adapted to the DEA framework described above². Figure 1 illustrates the production flow of the animal-feed obtained from food waste for the two producers. Herein, the food waste suppliers of each producer differed. In particular, Producer-A treated business food waste from manufacturing and wholesaling, while Producer-B treated business food waste from retail and service. In most cases, business food waste from retail and service contains more water and impurities than that from manufacturing and wholesaling; moreover, its nutritional composition is more unstable. Therefore, business food waste from retail and service is more difficult to

² We collected input-output data for the empirical analysis from two representative Japanese manufacturers of animal-feed from food wastes. The inputs and outputs used in the empirical analysis were selected based on our on-site investigation of the manufacturing process and the opinions of experts engaged in the manufacturing process there.

356 convert into animal-feed; moreover, in Japan, the number of producers treating business food
357 waste from retail and service is fewer than those treating business food waste from
358 manufacturing and wholesaling (MAFF, 2020b). Conversely, each of the two producers
359 produced dried animal-feed.³ Business food waste supplied by each food waste supplier was
360 collected by each producer using trucks; moreover, diesel oil was consumed at this time.
361 Thereafter, the collected food waste was separated from the packaging containers, heat-treated,
362 and converted into feed through a drying process.⁴ Heavy oil was consumed in the drying
363 process while electricity was consumed in the other processes.

³ Animal-feed from food waste could also be produced by drying, processing in liquid form, or silaging. See Sugiura et al. (2009) for the differences in production methods.

⁴ The equipment used in the drying process differed between the two companies: Producer-A utilized the indirect steam drying method; and Producer-B, the vacuum drying method.

Figure 1. Conversion of food waste into animal-feed by each producer (A and B)

Table 1 shows the descriptive statistics of the input–output data used here. In Table 1, the average values of electricity consumption and heavy oil consumption differed between Producer-A and Producer-B; this mainly occurred due to the difference in the equipment used in the drying process. Additionally, the scale of Producer-A was larger than that of Producer-B; hence, the two producers also demonstrated a huge difference in their average electricity consumption. Even though the average food waste collection by the two producers differed insignificantly, the average animal-feed production differed significantly due to the difference in the food waste collection channels between the two producers. Business food waste from retail and service contains more water and impurities than that from manufacturing and wholesaling; thus, the weight of the former decreases more than the latter after the drying process.

To better understand the different properties of the food waste treated by each producer, the monthly “quality of food waste (QFW)” could be calculated for each producer by dividing the animal-feed production by the food waste collection. The QFW value was mainly determined by the moisture content and the existence of separation; moreover, if the collected food waste contained excessive moisture or impurities, the QFW value would be low. In fact, the average QFW value for Producer-A was 0.66; and for Producer-B, 0.13. Considering this

difference in QFW values, we could confirm that the food waste collected by Producer-B contained more water and impurities than that collected by Producer-A.

Additionally, we could confirm the difference in the food waste collection channels between Producers A and B by comparing the difference in the coefficient of variation (CV) of each input-output by month. The CV was calculated by dividing the standard deviation of each input-output by each average value as in Table 1. The calculated CV of Producer-B (0.15 for the food waste collection; 0.15 for the animal-feed production) was higher than that of Producer-A (0.07 for the food waste collection; 0.10 for the animal-feed production). This difference in CV values between the two producers implied that Producer-A collected food waste more stably than Producer-B. In fact, Producer-A, which treated business food waste from manufacturing and wholesaling, collected from 15 large-scale bakery and confectionery factories, thus easily maintaining a stable collection volume. Conversely, Producer-B, which treated business food waste from retail and service, collected from approximately 200 small and medium-sized restaurants and retailers; hence, a stable amount of food waste collection could not always be expected.

Table 1. Descriptive statistics of the input-output data for each producer

		Electricity	Heavy oil	Diesel oil	Food waste collection	Animal-feed production
	Unit	kWh	L	L	t	t
Producer-A	Mean	20004.8	15336.5	6449.0	539.8	351.5
	S.D.	2127.5	2985.6	959.6	39.2	35.4
	Minimum	15552.0	10227.0	4219.0	469.0	275.0
	Maximum	25626.0	20946.0	7734.0	646.0	429.0
Producer-B	Mean	93.0	22219.5	5617.5	529.9	69.4
	S.D.	14.4	2701.0	699.8	79.9	10.7
	Minimum	70.0	12600.0	3503.8	243.8	32.5
	Maximum	119.0	26800.0	6798.8	638.5	91.5

5. Results and discussion

5.1. Technical, pure technical, and scale efficiencies

Table 2 shows the technical efficiency (TE), pure technical efficiency (PTE), scale efficiency (SE), and RTS by month for each producer. From Table 2, it is clear that Producers A and B had 8 and 2 technically efficient (i.e., TE = 1) months, respectively, during the analysis period. In other words, there were 35 and 41 months of inefficient production activities considering Producers A and B, respectively. The average TE for Producer-A was 0.85; and for Producer-B, 0.73; this indicated that the gap in monthly production efficiency for Producer-B was larger than that for Producer-A.

The PTE is an efficiency score purely for production technology without considering the effect of production scale. Table 2 shows that 18 months in Producer-A and 6 months in Producer-B demonstrated pure technical efficiency (i.e., $PTE=1$) during the analysis period. Note that the PTE had been improving year by year for each producer, respectively. The average PTE for Producer-A and Producer-B in 2018 was 0.85 and 0.75, respectively; and in 2020 was 0.99 and 0.92, respectively, being considerably higher than that of the two previous years. This could be attributed to the operational management of both companies for improving the efficiency of production. In fact, the plant manager of Producer-A actively worked toward improving production efficiency by adopting the environmental management system promoted by the Ministry of the Environment (i.e., Eco-Action 21); hence, the successful outcome was definitely reflected in the PTE score.

SE indicates the monthly efficiency of the production scale, where $SE = 1$ indicates an optimal production scale. The average SE for Producer-A was 0.93; and for Producer-B, 0.90, implying that both producers had inefficiencies considering the scale of their production. The average SE of Producer-B was lower than that of Producer-A. Additionally, the CV of the SE in Producer-B (1.22) was greater than that of SE in Producer-A (1.15). The differences in the mean and the CV of the SE between the two producers indicated that Producer-B demonstrated greater variation in the monthly production scale and had greater scale inefficiencies. This is

because, as described in Section 4, Producer-B collected food waste mainly from restaurants and retail industries; moreover, it was difficult to obtain food waste constantly. Further, it is noteworthy that since April 2020 when the COVID-19 infection began spreading, only the SE scores for Producer-B had fallen significantly, while the PTE was maintained at a high level. In Japan, a “State of Emergency” was declared April 2020 onward due to the COVID-19 pandemic; hence, the amount of food waste decreased as a result of restrictions on visiting restaurants. Therefore, Producer-B, which mainly collected food waste from food retailers and restaurants, was unable to collect a stable volume of food waste. In contrast, the SE of Producer-A remained high after April 2020, indicating that Producer-A was unaffected by COVID-19. This is because food manufacturers were the main suppliers of food waste for Producer-A; hence, they were able to stably collect food waste during the COVID-19 outbreak.

Table 2 also provides the nature of the RTS for each producer, monthly. In the months where the nature of the RTS was an IRS, the production scale needed to be increased because it was considerably small to obtain economies of scale (Shi et al., 2010). Conversely, in the months when the nature of the RTS was a DRS, the production scale was considerably large, with the occurrence of congestion; hence, the production scale required a reduction (Shi et al., 2010). As per Table 2, Producers A and B were characterized by 24 and 35 months, respectively, with an IRS, implying that both producers could have gained economies of scale by expanding

their production over many months. In particular, Producer-B was characterized by a greater number of months with an IRS than Producer-A due to the instability in food waste collection as mentioned above. Therefore, expanding the production scale of producers treating food waste from retail and service, such as Producer-B, is more important toward improving production efficiency.

Figure 2 shows a scatter plot of the animal-feed production and the SE; for both producers, it can be observed that the SE tended to be higher at a larger production scale. Consequently, the TE also tended to increase with an expansion in the production scale (see Figure A.1(a) in the Appendix⁵). Therefore, expanding the production scale is critical toward improving the efficiency in producing animal-feed from food waste. A comparison of the coefficients of determination for each producer as in Figure 2 also suggests that expanding the production scale of producers such as Producer-B, is particularly important for improving production efficiency.

⁵ Note that PTE does not have a correlation with production scale (see Figure A.1(b)).

Table 2. Monthly efficiency scores and returns to scale for each producer

Year. Month	<u>Producer-A</u>				<u>Producer-B</u>			
	TE	PTE	SE	RTS	TE	PTE	SE	RTS
2017.01	0.720	0.867	0.831	IRS	0.667	0.765	0.873	IRS
2017.02	0.847	1.000	0.847	IRS	0.882	0.887	0.995	DRS
2017.03	0.813	0.862	0.944	IRS	1.000	1.000	1.000	CRS
2017.04	0.767	1.000	0.767	IRS	0.851	0.856	0.993	DRS
2017.05	0.745	0.833	0.894	IRS	0.646	0.734	0.881	IRS
2017.06	0.846	0.871	0.972	DRS	0.851	1.000	0.851	IRS
2017.07	0.778	0.779	0.998	IRS	0.679	0.730	0.931	IRS
2017.08	1.000	1.000	1.000	CRS	0.675	0.773	0.873	IRS
2017.09	0.843	0.866	0.974	IRS	0.762	0.772	0.987	IRS
2017.10	1.000	1.000	1.000	CRS	0.740	0.749	0.988	DRS
2017.11	0.884	1.000	0.884	IRS	0.696	0.756	0.921	IRS
2017.12	0.767	0.788	0.973	IRS	0.833	0.861	0.968	DRS
2018.01	0.685	0.731	0.937	IRS	0.707	0.726	0.973	IRS
2018.02	0.775	0.802	0.967	IRS	0.746	0.782	0.955	IRS
2018.03	0.785	0.794	0.988	DRS	0.748	0.750	0.997	DRS
2018.04	0.819	0.828	0.988	DRS	0.753	0.770	0.977	IRS
2018.05	0.855	0.859	0.995	DRS	0.681	0.684	0.997	DRS
2018.06	0.727	0.798	0.912	IRS	0.650	0.684	0.950	IRS
2018.07	0.686	0.689	0.995	DRS	0.623	0.716	0.870	IRS
2018.08	0.870	0.917	0.948	IRS	0.637	0.749	0.851	IRS
2018.09	0.781	1.000	0.781	IRS	0.621	0.750	0.829	IRS
2018.10	0.842	0.845	0.997	DRS	0.741	0.797	0.930	IRS
2018.11	0.899	0.910	0.988	IRS	0.764	0.806	0.948	IRS
2018.12	0.986	1.000	0.986	DRS	0.754	0.757	0.996	IRS
2019.01	1.000	1.000	1.000	CRS	0.714	0.754	0.947	IRS
2019.02	1.000	1.000	1.000	CRS	0.689	0.776	0.888	IRS
2019.03	0.789	0.796	0.991	DRS	0.747	0.818	0.913	IRS
2019.04	0.834	0.930	0.896	IRS	0.653	0.789	0.828	IRS
2019.05	0.886	1.000	0.886	IRS	0.743	0.780	0.952	IRS
2019.06	0.869	1.000	0.869	IRS	0.773	0.824	0.938	IRS
2019.07	0.967	0.974	0.993	DRS	0.733	0.807	0.908	IRS
2019.08	0.881	0.881	1.000	CRS	0.761	0.838	0.908	IRS
2019.09	0.868	0.868	1.000	CRS	0.804	0.832	0.966	IRS

2019.10	0.652	0.821	0.794	IRS	0.779	0.787	0.990	IRS
2019.11	0.762	1.000	0.762	IRS	0.729	0.806	0.905	IRS
2019.12	0.909	0.963	0.943	IRS	0.660	0.761	0.867	IRS
2020.01	0.833	1.000	0.833	IRS	0.773	0.809	0.956	IRS
2020.02	0.792	1.000	0.792	IRS	0.692	0.800	0.864	IRS
2020.03	1.000	1.000	1.000	CRS	1.000	1.000	1.000	CRS
2020.04	1.000	1.000	1.000	CRS	0.574	1.000	0.574	IRS
2020.05	1.000	1.000	1.000	CRS	0.502	1.000	0.502	IRS
2020.06	1.000	1.000	1.000	CRS	0.611	1.000	0.611	IRS
2020.07	0.813	0.903	0.901	IRS	0.664	0.858	0.773	IRS
MEAN	0.851	0.911	0.934		0.728	0.811	0.897	
MAX	1.000	1.000	1.000		1.000	1.000	1.000	
MIN	0.652	0.689	0.947		0.502	0.684	0.734	
S.D.	0.098	0.091	0.076		0.096	0.087	0.109	

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469 Figure 2. Scatter plot of monthly animal-feed production and SE for each producer

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5.2. Slack proportions

The SP, calculated in Eqs. (10) and (11), indicates the technology improvement potential of the prevailing technology level of each input and output (Eguchi et al., 2021). In other words, the magnitude of the SP could be directly interpreted as the magnitude of inefficiency, considering a specific input and output. Figure 3 summarizes the monthly SP with respect to each of the three inputs (i.e., electricity, heavy oil, and diesel oil consumption) for each producer.⁶ Going ahead, the plant managers of each producer could refer to Figure 3 to implement improvements for enhancing production efficiency.

Figure 3 shows that in Producer-A, the average SP value was the highest (i.e., inefficient) for heavy oil, while it also had high variability. Therefore, in Producer-A, improving the efficiency considering the use of heavy oil could contribute most toward enhancing production efficiency. In particular, efficiency, considering the use of heavy oil could be improved by introducing more fuel-efficient drying equipment. In fact, Producer-A introduced more fuel-efficient drying equipment in 2019; the effectiveness is observable in Figure 3, where the SP value considering heavy oil is clearly lower (i.e., more efficient) since 2019. Figure 3 also shows that the average SP value was the lowest (i.e., efficient) for diesel oil; moreover, its

⁶ We also calculated the SP for animal-feed production using Eq. (11). However, all SP values equaled to zero; hence, they are not listed in Figure 3.

variability was the smallest in Producer-A. This is because Producer-A, that treated business food waste from manufacturing and wholesaling, could easily estimate in advance the amount of food waste and its time of occurrence considering the food manufacturers; hence, it could flexibly adjust the collection route and number of trucks required for collection.

In contrast, in Producer-B, the average SP value was the lowest (i.e., efficient) for heavy oil and the highest (i.e., inefficient) for diesel oil. Therefore, Producer-B had the highest inefficiency considering the consumption of diesel oil in the food waste collection process. This is because Producer-B, that treated business food waste from retail and service, could not flexibly adjust collection routes and the number of trucks required as it is difficult to predict in advance the amount of food waste that could be collected from retailers and restaurants. Furthermore, considering Figure 3, we could confirm that the SP value for diesel oil used in Producer-B was particularly high after April 2020. The supply of food waste to Producer-B became further unstable due to a dramatic decrease in the volume of food waste in restaurants due to the COVID-19 pandemic. Consequently, the collection efficiency of food waste considering diesel trucks decreased significantly. It is also clear from Figure 3 that the SP values for heavy oil and electricity use increased after April 2020, similar to the case for diesel oil. This is because the size of equipment used cannot be changed in response to the amount of food waste collected; hence, the amount of animal-feed produced per unit of heavy oil and electricity

507 consumed decreased during the COVID-19 pandemic.

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Year. Month	Producer A			Producer B		
	Electricity	Heavy oil	Diesel oil	Electricity	Heavy oil	Diesel oil
2017.01	0.32	0.37	0.15	0.47	0.27	0.26
2017.02	0.18	0.26	0.02	0.25	0.00	0.10
2017.03	0.21	0.28	0.07	0.00	0.00	0.00
2017.04	0.23	0.35	0.11	0.31	0.03	0.12
2017.05	0.25	0.37	0.14	0.40	0.28	0.38
2017.06	0.16	0.30	0.00	0.17	0.00	0.28
2017.07	0.25	0.33	0.09	0.38	0.22	0.37
2017.08	0.00	0.00	0.00	0.41	0.23	0.34
2017.09	0.17	0.28	0.02	0.30	0.07	0.34
2017.10	0.00	0.00	0.00	0.30	0.14	0.34
2017.11	0.08	0.26	0.00	0.35	0.18	0.38
2017.12	0.26	0.31	0.12	0.25	0.05	0.20
2018.01	0.32	0.44	0.18	0.40	0.17	0.31
2018.02	0.26	0.39	0.03	0.33	0.11	0.31
2018.03	0.26	0.37	0.02	0.31	0.16	0.29
2018.04	0.20	0.33	0.01	0.32	0.13	0.29
2018.05	0.16	0.26	0.01	0.33	0.24	0.39
2018.06	0.22	0.34	0.26	0.39	0.27	0.40
2018.07	0.33	0.39	0.23	0.38	0.31	0.45
2018.08	0.09	0.13	0.17	0.41	0.29	0.39
2018.09	0.18	0.21	0.27	0.35	0.29	0.50
2018.10	0.09	0.18	0.20	0.22	0.13	0.43
2018.11	0.08	0.11	0.12	0.16	0.17	0.38
2018.12	0.01	0.00	0.03	0.17	0.26	0.31
2019.01	0.00	0.00	0.00	0.22	0.30	0.34
2019.02	0.00	0.00	0.00	0.27	0.29	0.38
2019.03	0.17	0.24	0.23	0.20	0.19	0.37
2019.04	0.11	0.21	0.17	0.30	0.36	0.39
2019.05	0.04	0.16	0.15	0.19	0.21	0.38
2019.06	0.06	0.18	0.15	0.16	0.14	0.37
2019.07	0.01	0.09	0.00	0.22	0.22	0.37
2019.08	0.12	0.09	0.15	0.22	0.21	0.29
2019.09	0.14	0.15	0.10	0.09	0.16	0.33
2019.10	0.29	0.32	0.43	0.08	0.24	0.35
2019.11	0.25	0.26	0.20	0.15	0.30	0.37
2019.12	0.11	0.09	0.08	0.23	0.39	0.40
2020.01	0.19	0.15	0.16	0.12	0.28	0.29
2020.02	0.22	0.17	0.23	0.21	0.31	0.41
2020.03	0.00	0.00	0.00	0.00	0.00	0.00
2020.04	0.00	0.00	0.00	0.55	0.26	0.46
2020.05	0.00	0.00	0.00	0.57	0.41	0.51
2020.06	0.00	0.00	0.00	0.29	0.34	0.54
2020.07	0.22	0.21	0.14	0.24	0.30	0.47
MEAN	0.15	0.20	0.10	0.27	0.21	0.34
MAX	0.33	0.44	0.43	0.57	0.41	0.54
MIN	0.00	0.00	0.00	0.00	0.00	0.00
S.D.	0.10	0.13	0.10	0.13	0.11	0.11

Figure 3. Monthly slack proportions for each producer

As mentioned in Section 4, the QFW value was mainly determined by the moisture content and impurities present. If the collected food waste is of low quality, a substantial amount of energy is required for removing impurities and for heating and drying. Therefore, we could assume that the QFW value significantly affects the monthly efficiency score and SP. Figure 4 shows the scatter plot of the monthly QFW and SP. Considering Figure 4, it is clear that the SP and QFW are negatively correlated for all inputs for each producer. In other words, an improvement in the QFW could lead to an improvement in efficiency for all inputs. Table 3 summarizes the results of the single regression analysis considering the monthly QFW values for each producer as the independent variables and the monthly SP values for the input of each producer as the dependent variables. The results of the single regression analysis in Table 3 demonstrate that a significant negative relationship exists between the QFW and all other SPs of the two producers, except for the SP considering heavy oil in Producer-A. Furthermore, by comparing the magnitude of the parameters between the two producers, it is clear that the QFW has more influence on each SP value in Producer-B. In other words, for producers treating food waste from retail and service, such as Producer-B, improving the QFW is particularly important toward improving the efficiency, considering the use of each input. In particular, an improvement in the QFW (i.e., a reduction in the moisture and impurity content) leads to an improved fuel efficiency of diesel trucks and reduced electricity and heavy oil consumption in the fractionation and drying processes.

Figure 4. Scatter plot of QFW and slack proportions for each producer

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Table 3. Estimations based on a regression analysis

Dependent variable	Producer-A			Producer-B		
	SP (Electricity)	SP (Heavy oil)	SP (Diesel oil)	SP (Electricity)	SP (Heavy oil)	SP (Diesel oil)
Constant	0.41*** (0.00)	0.35** (0.04)	0.36*** (0.00)	0.54*** (0.00)	0.68*** (0.00)	0.92*** (0.00)
Coefficient (QFW)	-0.4** (0.04)	-0.23 (0.37)	-0.4** (0.03)	-2.05** (0.02)	-3.57*** (0.00)	-4.42*** (0.00)
<i>N</i>	43	43	43	43	43	43
R squared	0.10	0.02	0.11	0.13	0.56	0.76

Note: Numbers in parentheses indicate the p value.

Superscript *** represents significance at the 1% significance level.

Superscript ** represents significance at the 5% significance level.

Superscript * represents significance at the 10% significance level.

6. Conclusion and policy implication

Here, a DEA was applied considering the monthly input–output data of two producers of animal-feed obtained from food waste in Japan to quantify the production efficiency in the process of converting food waste into animal-feed and identify the causes contributing to the inefficiency. Based on the results of estimated TE, the two producers demonstrated numerous months (i.e., Producer-A: 35; Producer-B: 41 months) characterized by inefficient production activity, especially Producer-B, where the gap in the monthly production efficiency was larger than that in Producer-A. The estimated SE and RTS values demonstrate that both producers had production inefficiencies related to scale, which could be improved by increasing the production scale. Producer-B demonstrated greater variation in the production scale and greater inefficiency considering the scale, mainly brought about by differences in the food waste collection channels. We also estimated the monthly SP for each producer to determine the level of inefficiency considering each of the three inputs. The results indicated specific inefficiencies brought about by the use of heavy oil in Producer-A and diesel oil in Producer-B. A negative correlation was also identified between the QFW and the SP for each input considering each producer, indicating that an improvement in the QFW could help improve the efficiency considering all inputs. The QFW was particularly influential, considering an improvement in the efficiency of the three inputs of Producer-B. Based on the findings of the empirical analysis conducted, we could discuss a few policy implications for policy makers globally who are

attempting to promote the use of food waste as animal-feed, and for the Japanese government, which is working to increase the production volume of animal-feed obtained from food waste.

As mentioned in Section 1, the conversion of food waste into animal-feed is currently not widely practiced, except in some East-Asian countries such as Japan and Korea, due to the risk of spreading diseases such as foot-and-mouth disease and African swine fever. However, the large amount of food waste during the consumption stage is a challenge for all developed countries, and many studies have examined the feasibility of introducing the production of animal-feed to food waste in various countries as an effective solution, as shown in Section 2; the first step toward this is sanitation management. The case studies for Japan and Korea have proved that a thorough heat treatment could help prevent the spread of diseases caused by the use of animal-feed obtained from food waste. Each country needs to first overcome sanitation issues by referring to the laws and technical systems adapted in Japan and Korea. Thereafter, governments could increase the number of producers that treat business food waste from manufacturing and wholesaling, such as Producer-A; this is because such waste occurs in larger quantities than business food waste from retail and service; moreover, the production efficiency is relatively stable and less affected by exogenous shocks (e.g., COVID-19), as shown here.

In Japan, subsidies are provided to eco-feed producers based on its increased use to increase the recycling of food waste and expand the production of animal-feed. Our empirical analysis proved that such a subsidy is reasonable, as it demonstrates that expanding the production scale helps improve the production efficiency of the feed-conversion process. The Japanese government also provides more subsidies to producers such as Producer-B to increase the production of animal-feed from business food waste from retail and service. Our study shows that expanding the production scale of producers treating food waste from retail and service is particularly important for improving their production efficiency. Therefore, the subsidy policy of the government to prioritize producers engaged in the conversion of business food waste from retail and service to animal-feed is also considered to be reasonable.

Our empirical analysis showed that there was a monthly technical gap in the production efficiency of each producer; hence, the government needs to have additional policies to encourage the production of animal-feed from food waste. The production efficiency of the feeding process can be enhanced not only by improving efficiency considering the production scale (i.e., SE), but also by improving the technical efficiency considering each input (i.e., SP) by improving the QFW. For example, retailers and restaurants could separate food waste from combustible waste in advance to improve the SP, considering electricity consumed to separate impurities in producers such as Producer-B. Optimization of food waste collection routes using

information technology could also help improve the SP for diesel consumption, especially in producers such as Producer-B. Additionally, incentives for food waste generators to choose recycling rather than incineration are also important to ensure the widespread use of food waste as animal-feed. For example, if the government sets the collection cost of food waste by incineration companies to be costlier than that of food waste recycling companies, producers of food waste would naturally choose to recycle such waste.

Finally, the study found that the COVID-19 pandemic severely impacted producers such as Producer-B. The scale efficiency of Producer-B has been extremely low since April 2020, suggesting that the company is not doing well financially. The government needs to urgently implement appropriate support policies not only for restaurants, but also for producers engaged in resource recycling further downstream in the supply chain, such as those producing animal-feed from food waste.

This study had limitations considering that the input–output data was not available for numerous producers; it focused on the data only from two producers located in Japan. However, since 26 eco-feed producers existed in Japan as of 2020, additional data could be obtained for future studies. Furthermore, this study focused on production efficiency; however, it was unable to evaluate environmental efficiency or cost-efficiency. As the efficiency analysis framework

609 using a DEA could also consider the environmental and economic aspects of production
610 activities, the analysis could be further developed considering these perspectives.

611

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621

622 **Consent to Publish**

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625 **Authors Contributions**

626 **Tomoaki Nakaishi:** Conceptualization; Funding acquisition; Data curation; Resources; Formal
627 analysis; Investigation; Methodology; Project administration; Software; Validation;

628 Visualization; Writing - original draft; Writing - review & editing. **Hiroataka Takayabu:**

629 Conceptualization; Formal analysis; Investigation; Methodology; Software; Validation;

630 Visualization; Writing - original draft; Writing - review & editing.

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634

635 **Competing Interests**

636 There are no conflicts of interest to declare.

637

638 **Availability of data and materials**

639 The data used in the empirical analysis was obtained directly from two typical animal-feed from

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641 disclosed without our approval.

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