Applying Techno-economic Analysis to Evaluate the Economic Value of Residue Reuse of Makino Bamboo (Phyllostachys makinoi)

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Abstract

The bamboo industry in Taiwan was very prosperous in the early days. However, with the development of the industry, bamboo was replaced by plastics, metals, and composite materials. There are different ways to process bamboo waste from the bamboo processing industry. This study aimed to analyze the economic benefits of different processing methods for Makino waste materials using techno-economic analysis and cost-benefit analysis. This study divided the treatment methods into two categories: (a) remove, discard, and no longer use and (b) reuse to make fuel rods for sale. Category (a) includes one scenario: removing and sending the waste materials to the joss paper processing manufacturer to proceed with incineration and burial. Category (b) was divided into 6 scenarios according to whether they need to bear the cost of equipment and whether they need to hire additional full-time employees. The results show that different analysis methods all point out that Scenario 7 (the manufacturer does not have to bear the cost of equipment and does not hire additional professional employees) is the best solution. If using the net present value method, present value cost method, net annual value method, and annual cost method for evaluation, then scenario 6 (the manufacturer does not have to bear the equipment costs and hire additional professional manpower) and scenario 7 are better than scenario 1 (the bamboo waste was removed). If using the net present value rate method, profitability index method, and self-liquidating ratio for evaluation, then the results show that only scenario 7 is profitable, and no other scenarios should be selected. This means that the production of fuel rods from bamboo waste materials can increase the material output value, help manufacturers create economic benefits, and solve the regional environmental problems caused by the long-term accumulation of waste materials. Therefore, to minimize the waste of resources and through the government subsidizing the cost of equipment, the implementation of the applications of the circular economy can achieve a balance between environmental protection and socioeconomic benefits. It is recommended to apply industry-academia cooperation, hiring students from relevant departments to reduce labor costs and enable students to understand the bamboo industry.

1 Introduction

The United Nations Intergovernmental Panel on Climate Change (IPCC) has speculated that global warming may reach 1.5°C between 2030 and 2052 if the current "economic development model" is maintained, and humankind will face more severe climate risks (IPCC, 2020). To maintain economic development while reducing the loss of natural resources and solving environmental problems, the concept of a circular economy has been developed. The circular economy can be defined as an economic model whose goal is to preserve value and efficiently utilize resources between environmental protection and socioeconomic benefits by minimizing the waste of resources (Murray, et al., 2017; Hofmann, 2019; Mastellone, 2020). To enable the sustainable use and development of natural resources, various countries legislate to expand the types and scope of waste disposal. By reducing and narrowing the material and energy cycles, the input of resources and waste emissions can be reduced to achieve the goal of reducing waste and recycling materials to enhance their economic value. (Liou, Y. H., 2011). Among the technologies applied to reduce waste materials for energy cycling, the production of solid fuel (refuse derived fuel 5, RDF-5) is currently the most common. The main characteristics of RDF-5 are its size, uniform density, increased heating value, easy transportation and storage, and convenient use. It can be directly applied to mechanical bed boilers, fluidized bed boilers, and power generation boilers as the main fuel or co-firing with coal. (Council of Agriculture, Executive Yuan, 2016; Ge and Wu, 2001; Wu and Ge, 2002).

In addition, the use of wood materials as biomass energy is a renewable energy source that the energy policies of EU and American countries have promoted and applied vigorously in the past ten years, especially since the RDF-5 wood pellets are widely made from the remaining wood residues. The wood pellets use high-temperature compression to crush finely ground wood to produce hard cylindrical particles (diameter 6–10 mm, length 10–20 mm; wood fuel rods refer to cylinders with a diameter of more than 16 mm). The production size and quality of wood pellets or wood fuel rods can be standardized. It has many advantages, such as a stable nature, small size for easy storage, transportation, and relatively low management costs, flame resistance, good heat energy efficiency, environmental protection function, renewability, ease of use, and less soot residual ash during the incineration process. It can be used not only as a source of heat and steam for households but also as an alternative to fossil fuel for the operation of electric energy (Lin and Pan, 2014). According to the World Bioenergy Association (WBA) survey of global biomass energy statistics, wood pellets are the fastest-growing biomass energy in the world, with global production increasing from 18.1 million metric tons in 2012 to 38.9 million metric tons in 2019. With an average annual growth rate of 11.6%, the global production volume in 2019 in Europe accounted for 54.8%, followed by the Americas at 31.6%, and Asia at 12.9%, and production in Asia grew the highest by 49% (WBA, 2020).

However, in the trend of world energy, Taiwan's current forestry policy focuses on conservation and lacks sufficient forest resources to develop wood pellets. The industry has not yet flourished in Taiwan but it has rich bamboo resources. According to the Forestry Bureau "The Fourth National Forest Resources Inventory Report", Taiwan's pure bamboo forest area is approximately 130,000 ha, accounting for approximately 6.1%. If mixed with wood and bamboo, the area can reach 257,000 ha, approximately 11.8% of Taiwan's forest cover area (Forestry Bureau, 2020). Bamboo grows fast and has strong fecundity and a short growth period. The processing and production of bamboo and bamboo products are important economic lifelines of rural economies in Asia and Central and South America. In addition, the bamboo processing industry in Taiwan was quite prosperous in the early days. Before the 1970s, it mainly focused on producing bamboo shoots and manufacturing bamboo household products for domestic sales. There are many processing factories related to the bamboo industry. Moreover, the government assisted in building factories and helped with exportation. In 1980, the gross export value of the bamboo industry reached US$117,412,000 (Lee and Lee, 1993). However, with the development of industry, bamboo was replaced by plastic, metal, and composite materials and by the low-cost, high-quality bamboo products developed in China and Southeast Asian countries with low labor costs and rich bamboo resources, causing numerous domestic bamboo processing factories to move out. The competitiveness and output of the bamboo processing industry have declined rapidly until now. The decline of the bamboo processing industry can be seen from approximately 1,500 registered manufacturers in its heyday to less than one-third of the number in 1993 and less than 100 in 2004 to understand the decline of the bamboo processing industry (Lin, et al., 2003). It has been more than 20 years since competitiveness declined sharply. However, there are still a few manufacturers with rich processing experience who have not followed the trend to move out and continue to operate until now. These manufacturers are most concentrated in the Jhushan area of Nantou County in the central region, forming an industrial cluster.

Bamboo processing plants generate a large amount of waste material in the production process. In the early days, waste materials were sent to local traditional paper mills as raw materials for the production of joss paper. However, due to the tightening discharge of wastewater in environmental regulations, the joss paper manufacturers could not continue to operate and were closed and stopped recycling and processing waste materials, and then waste materials could not be removed normally, resulting in long-term accumulation and many other problems, such as environmental and industrial management difficulties. According to an interview survey conducted by the Forestry Research Institute on bamboo processing waste manufacturers in the Jhushan area of Nantou County in 2015, the total demand for bamboo in this region in 2014 was approximately 37,000 tons (equivalent to 61.58 million Taiwan catty), with an average of 3,080 metric tons/month. The amount of bamboo waste was approximately 8,395 metric tons/year (equivalent to 13,995,600 Taiwan catty/year), with an average of 700 metric tons/month, and there are still a number of reusable bamboo processing waste materials. These materials can be used to produce fuel pellets (rods), which can increase the density of materials and have the characteristics of increasing the heat of combustion and flame resistance. If they are applied to power and heat generation, reducing the proportion of thermal power generation and nuclear power generation, they can not only recycle waste bamboo materials but also reduce emissions of carbon dioxide and other waste gases. This method is also less restricted by seasons and regions, and it can enhance the benefits of energy security and sustainable use of resources.

To solve the problem of disposal of bamboo waste materials for the bamboo processing industry and to implement the circular economy goal of resource utilization at the same time, this study case is that the Taiwan Forestry Research Institute assisted a traditional manufacturer of bamboo sticks for BBQ in the Jhushan area of Nantou County through technical guidance to build bamboo fuel pellets or fuel rod production equipment and technology and make bamboo fuel pellets (rods) from bamboo waste materials generated in the processing stage to solve the problems of the accumulation of bamboo waste materials due to the suspension of resource recycling and utilization in joss paper manufacturers, resulting in space occupation, environmental damage, and other operational difficulties. In addition, the production of bamboo fuel pellets can also increase the economic interests of manufacturers. The purpose of this study is to evaluate the economic benefits of this model in assisting manufacturers in producing bamboo fuel pellets (rods) from bamboo waste materials through techno-economic analysis (TEA) and cost-benefit analysis (CBA) as a decision-making reference to promote the construction of a regional circular economy industrial model for bamboo waste materials.

2 Materials and methods

2.1. Study case background

The bamboo processing manufacturer of this study case is located in Jhushan Township, Nantou County. They use Makino bamboo as the main raw material to produce bamboo sticks for BBQ. The process of producing bamboo sticks is as follows: (1) remove the bamboo joints and then cut and slice bamboo tubes according to the size requirements; (2) bundle the cut bamboo slices into bunches and soak them in water to soften; (3) after softening, use a slicing machine to thin the bamboo slices to make semifinished bamboo sticks; (4) fumigate the semifinished products for bacteriostatic purposes; (5) then use steam heat to dry the semifinished products; and (6) after drying, the semifinished products were sanded, trimmed and sharpened and then packed. During the process, removing bamboo joints, cutting bamboo tubes, and thinning bamboo slices will produce waste materials such as bamboo joints and bamboo slivers. These waste materials were impossible to use for purposes other than recycling to make joss paper in the past. If they are not effectively removed, they will easily accumulate in large quantities and cause environmental problems (Fig. 1).

To solve these problems, the Taiwan Forestry Research Institute conducted a preliminary trial of the heat value of bamboo fuel pellets (rods), and the average heat value reached 4,300 cal/g, which met the basic need if used as fuel pellet energy. Therefore, the institute provided technical guidance to assist in the construction of the process for producing bamboo fuel pellets (rods) from bamboo waste materials. The equipment consists of three modules: crushing, drying, and pelletizing (rods). The process sequence of bamboo fuel pellets (rods) is described as follows: (1) Crushing operation: crush the bamboo waste materials into 1–2 mm uniform granular materials; (2) Drying operation: use the drying system to reduce the moisture content of the granular materials to 10–15%; (3) Pelletizing operation: after drying, the material was sent to the pelletizing system for pelletizing (rods); (4) Cooling operation: the bamboo fuel pellets (rods) products that were initially formed by the pelletizing system need to be kept at room temperature before packaging and shipping.

2.2. Analysis method

This study applied techno-economic analysis and cost-benefit analysis to evaluate the economic benefits of using bamboo waste materials to produce bamboo fuel pellets (rods). The techno-economic analysis is one of the evaluation methods for engineering technology projects. The study areas include technical and economic issues at the national, industrial, enterprise, and engineering levels, aimed at addressing the economic issues in technical or engineering projects to explain the economic significance of the projects and bring forward a feasibility evaluation (He and Ren, 2019). Techno-economic analysis is mainly composed of three knowledge aspects, including (1) the knowledge of the rules and characteristics of technological innovation, which are the principles, motivations, organizational systems, precipitating and promoting factors; (2) the knowledge of the interaction or influence between technology and economy, aimed at focusing on the contribution of technology to economic growth, including the analysis of its principles, contribution rates, etc.; and (3) the knowledge of application, which mainly includes the evaluation of the economic effect of technology, the economic concept of the process of technology application, the methods of evaluating the economy of technology practices, the economic benefits of technical activities, and the data receiving and processing, etc. (He and Ren, 2019; Zhang et al., 2017). Cost-benefit analysis is one of the important economic decision-making methods for traditional economic analysis to evaluate whether investment decisions are feasible. It provides an objective and rational framework to estimate the use of additional resources (costs) to compare the recovery benefits and evaluate the appropriateness of implementing this decision. CBA not only considers the impact of the budget on the plan but also considers the positive and negative results of the decision to seek the greatest benefit at the lowest cost (Keilty, 2001). There are many cost-benefit analysis methods if adding techno-economic analysis for project evaluation, and they can be divided into the net present value method, net present value rate method, internal rate of return method, external rate of return method, present value cost method, net annual value method, annual cost method, profitability index method, self-liquidating ratio, dynamic investment payback period, etc. (Khootama et al., 2018). Each analysis method is described as follows:

(1) Net Present Value Method (NPV)

The net present value index is one of the most important indicators for the dynamic evaluation of investment projects. This index requires examining the annual cash flow during the life of the projects. The net present value is the cumulative sum of the present value of each year's net cash flows discounted to the same point in time (usually at the beginning) according to a certain discount rate. For a single item of the project, when NPV ≥ 0, the item should be accepted; when NPV < 0, the item should be rejected (He and Ren, 2019). The formula for the net present value is as follows:

$$NPV = \sum_{t=0}^{n} (C_I - C_O)_t (1 + i_0)^{-t} = \sum_{t=0}^{n} \left(C_I - K - C_O^{'}\right)_t (1 + i_0)^{-t}$$

In the formula, *NPV* is the net present value; C_{It} is the cash inflow in year *t*; C_{ot} is the cash outflow in year *t*; *K* is the investment expenditure in year t; $C_O^{'}$ is the cash outflow other than investment expenditure in year *t*; *n* is the lifespan of the item; and $i_0$is the benchmark discount rate.

(2) Net Present Value Rate Method (NPVI)

When comparing multiple projects, although the net present value method can reflect the profit and loss of each project, it cannot reflect the efficiency of the utilization of capital because the investment amount is not considered. The net present value rate method is the ratio of the net present value of the project and the present value of the total investment, also known as the net present value index, that is, the net present value brought by the unit of investment present value (He and Ren, 2019). The formula for the net present value rate is as follows:

$$NPVI = \frac{NPV}{K_P} = \frac{\sum_{t=0}^{n} (C_I - C_O)_t (1 + i_0)^{-t}}{\sum_{t=0}^{n} K_t (1 + i_0)^{-t}}$$

In the formula, *NPVI* is the net present value index; *NPV* is the net present value; K_p is the present value of the total investment; C_{It} is the cash inflow in year *t*; C_{ot} is the cash outflow in year *t*; K_t is the investment expenditure in year *t*; *n* is the lifespan of the item; and i_0 is the benchmark discount rate.

(3) Present Value Cost Method (PC)

When comparing multiple projects, if the output value of each project is the same or can meet the same needs but the output benefit is difficult to estimate, the present value cost method can be used to compare the advantages and disadvantages. The project with the smallest present cost value among multiple projects is the best, but the economic feasibility of a single project cannot be assessed (He and Ren, 2019). The formula for the present value cost method is as follows:

$$PC = \sum_{t=0}^{n} C_{0t} (1 + i_0)^{-t} - C_{It} (1 + i_0)^{-t}$$

In the formula, *PC* is the present value of cost; C_{It} is the cash inflow in year *t*; C_{ot} is the cash outflow in year *t*; *n* is the lifespan of the item; and i_0 is the benchmark discount rate.

(4) Net Annual Value Method (NAV)

The net annual value allocates the net present value of the project to the equivalent annual value of each year over the lifespan through the conversion of the equivalent value of capital. When NAV ≥ 0, the item is acceptable in terms of economic effects; when NAV < 0, then the item should be rejected in terms of economic effects (He and Ren, 2019). The formula for net annual value is as follows:

$$NAV = NPV\frac{i_0(1+i_0)^n}{(1+i_0)^n-1} = \sum_{t=0}^{n}(C_I - C_O)_t(1+i_0)^{-t}\frac{i_0(1+i_0)^n}{(1+i_0)^n-1}$$

In the formula, *NAV* is the net annual value; *NPV* is the net present value; C_{It} is the cash inflow in year *t*; C_{ot} is the cash outflow in year *t*; *n* is the lifespan of the item; and i_0 is the benchmark discount rate.

(5) Annual Cost Method (AC)

The annual cost and the present value cost are both applied to the comparison of multiple plans, and the best project is the one with the smallest annual cost value (He and Ren, 2019). The formula for the annual cost method is as follows:

$$AC = PC\frac{i_0(1+i_0)^n}{(1+i_0)^n-1} = \sum_{t=0}^{n}C_{0t}(1+i_0)^{-t}\frac{i_0(1+i_0)^n}{(1+i_0)^n-1}$$

In the formula, *AC* is the annual cost; *PC* is the present value cost; C_{ot} is the cash outflow in year *t*; *n* is the lifespan of the item; and i_0 is the benchmark discount rate.

(6) Internal Rate of Return Method (IRR)

Although the net present value method is simple and easy to implement, it must have a base earning rate to calculate, and the internal rate of return method makes up for the deficiency of the net present value method. This method does not require a given discount rate in advance, and the calculation results can reflect the actual investment efficiency achieved by the project. The internal rate of return is the discount rate when the net present value is equal to zero. When $IRR \geq i_0$, the project is feasible in terms of economic effect; when $IRR < i_0$, the project is unacceptable in terms of economic effect (He and Ren, 2019). The formula for the internal rate of return method is as follows:

$$NPV\,(IRR) = \sum_{t=0}^{n}(C_I - C_O)_t(1+IRR)^{-1} = 0$$

In the formula, *IRR* is the internal rate of return; *NPV* is net present value; C_{It} is the cash inflow in year *t*; C_{ot} is the cash outflow in *year t*; and *n* is the lifespan of the item.

(7) External Rate of Return Method (ERR)

Since the internal rate of return method is used for calculation, it assumes that all net incomes earned over the life of the project can be reinvested, and the earning rate on reinvestment is equal to the internal rate of return of the project. However, due to the limitation of investment opportunities, this assumption is usually difficult to meet in the actual situation. This also causes the IRR formula of unconventional investment plans to have multiple solutions. The external rate of return method is a modified version of the internal rate of return method. It assumes that all net incomes obtained during the life of the project can be fully reinvested, but the earning rate on investment is equal to the benchmark discount rate, that is, the discount rate that makes the present value of a total investment equal to the final value of the total revenue. When *ERR* ≥ i_0, the project is feasible in terms of economic effect; when *ERR* < i_0, the project is unacceptable in terms of economic effect (He and Ren, 2019). The formula for the external rate of return method is as follows:

$$\sum_{t=0}^{n} NB_t(1+i_0)^{n-t} = \sum_{t=0}^{n} K_t(1+ERR)^{n-t}$$

In the formula, *ERR* is the external rate of return; NB_t is the net income in year *t*; K_t is the net investment in year *t*; n is the lifespan of the item; and $i_0$is the benchmark discount rate.

(8) Profitability Index Method (PI)

The profitability index method is the ratio of the present value of future cash flows to the investment amount, that is, the "total present value of cash inflows" that can be obtained for each dollar of "initial investment amount", also known as the Benefit Cost Ratio. The advantage is that it is easy to calculate and very effective for independent investment cases but may be disadvantageous for mutually exclusive investment cases. If *PI* ≥ *1*, the investment is accepted; if *PI* ≤ *1*, the investment is rejected; if *PI* = *1*, then accept or not, there is no difference. The formula for the profitability index method is as follows:

$$PI = \frac{\sum_{t=0}^{n} C_{It}(1+i_0)^{-t}}{\sum_{t=0}^{n} C_{Ot}(1+i_0)^{-t}}$$

In the formula, *PI* is the profitability index; C_{It} is the cash inflow in year *t*; $C_{ot}$is the cash outflow in year *t*; n is the lifespan of the item; and $i_0$is the benchmark discount rate.

(9) Self-Liquidating Ratio (SLR)

The self-liquidating ratio is the ratio of the total present value of the net cash inflows to the total present value of the cash outflows in each year, that is, the proportion of the cost spent that can be recovered from the net income. In contrast, (1-self-liquidating ratio) the non-self-liquidating portion of the project, the proportion of the cost incurred that cannot be reclaimed from net income. If *SLR* ≥ *1*, it means that the project is fully self-liquidating and the investment is accepted; if *0* < *SLR* < *1*, the project is not fully self-liquidating and needs other organizations (such as the government) to participate in the investment; if *SLR* ≤ *0*, then this plan is not accepted. The formula for the self-liquidating ratio method is as follows:

$$SLR = \frac{\sum_{t=0}^{n} C_{It}}{\sum_{t=0}^{n} C_{Ot}} \times 100\%$$

In the formula, *SLR* is the self-liquidating ratio; C_{It} is the cash inflow in year *t*; $C_{ot}$is the cash outflow in year *t*; and n is the lifespan of the item.

(10) Dynamic Investment Payback Period (T)

The investment payback period is the time it takes for the net income obtained from each year to compensate for all the investments after the project is put into operation, and the time value of the capital is also taken into consideration. The formula of the dynamic investment payback period method is as follows:

$$\sum_{t=0}^{T_p} (C_I - C_O)_t(1+i_0)^{-t} = 0$$

In the formula, T_p is the dynamic investment payback period; C_{It} is the cash inflow in year t; $C_{ot}$is the cash outflow in year t; and $i_0$is the benchmark discount rate.

3. Variable settings

3.1 Recycling cost and weight of bamboo waste

In recycling bamboo waste, the manufacturer needs to pay for the cost of recycling, assuming it is NT$2,000 per trip, one metric ton recycled per trip, and 18.13 metric tons per year (data provided by the manufacturer).

3.2 The durability and calculation period of the machine

In making fuel rods from bamboo waste, the durability of the crusher, dryer, and rod-making machine is assumed to be 20 years, and the calculation period is also assumed to be 20 years.

3.3 The input cost of equipment (crusher, dryer, rod-making machine)

In making fuel rods from bamboo waste, the input cost of the crusher and the rod-making machine is assumed to be NT$4.8 million, and the input cost of the dryer is NT$2.84 million.

3.4 Time used to make the fuel rods

In making fuel rods from bamboo waste, it takes 5 hours each time to put 828 kgs of bamboo waste into the crusher and then put it into the dryer. Each batch can process 15 kgs in 30 minutes, with a moisture content of approximately 61%, leaving approximately 320 kgs of the bamboo waste, and then it will take 1 hour to put 320 kgs of bamboo waste into the rod-making machine and 0.1 hours to pack.

3.5 The electricity used to make fuel rods

In making fuel rods from bamboo waste, the electricity consumption of bamboo waste in the crusher is assumed to be 65 kWh for 5 hours, and then the electricity consumption of the bamboo waste in the rod-making machine is assumed to be 13 kWh for 1 hour.

3.6 Electricity price

The electricity price in this study is set at NT$2.4492 per kWh based on the electricity price of industrial electricity in Taiwan (Taiwan Power Company, 2019).

3.7 The cost and time of packaging

In making fuel rods from bamboo waste, a bag of NT$40 can pack 800 kgs of fuel rods and takes 13.5 minutes.

3.8 Fuel rod prices

In making fuel rods from bamboo waste, the price of fuel rods is NT$2.8 per kg.

3.9 Labor costs

This study is divided into two cases. The first case is to hire a full-time employee to monitor crushers and other equipment for the production of fuel rods; the other case is not to hire a full-time employee, and the manufacturer directly assigned an existing worker to monitor the crushers. In the case of hiring a full-time employee to monitor the crusher, dryer, and rod-making machine, the salary is assumed to be NT$1,264 for 8 hours a day, 22 days a month, and 12 months a year (Ministry of Labor, 2020).

3.10 The benchmark discount rate

The benchmark discount rate for this study is set based on Taiwan's five-year government bond yield of 0.3940% (Taipei Exchange, 2020).

4. Project selection

4.1 Bamboo waste materials were transported, discarded, and no longer used

Since bamboo waste materials generated after making bamboo sticks cannot be reused, it is necessary to pay for recycling trucks to transport them. The truck may send them to the joss paper manufacturers for processing or be directly incinerated or buried (as shown in Fig. 5); the hypothetical situation is as follows:

Scenario 1: Bamboo waste materials were transported and sent to joss paper processing manufacturers for incineration and burial.

4.2 Bamboo waste was recycled into fuel rods for sale

The bamboo waste generated from making bamboo sticks was put into the crusher for crushing, then put into the dryer for drying, then put into the rod-making machine to form fuel rods, and finally packaged and sealed (as shown in Fig. 6). This study assumed that the cost of the machine and equipment is covered by the manufacturer; the manufacturer and the government each share half of the cost; and all the costs are entirely borne by the government. The labor cost is divided into hiring a full-time employee and the original factory employee; no additional full-time employee is needed. The hypothetical scenario is as follows:

Scenario 2: The manufacturer bears the cost of the machine and equipment and needs to hire additional full-time employees to handle the operation

Scenario 3: The manufacturer bears the cost of the machine and equipment and does not need to hire additional full-time employees to handle the operation

Scenario 4: The manufacturer bears half of the cost of the machine and equipment and needs to hire additional full-time employees to handle the operation

Scenario 5: The manufacturer bears half of the cost of the machine and equipment and does not need to hire additional full-time employees to handle the operation

Scenario 6: The manufacturer does not need to bear the cost of machines and equipment and needs to hire additional full-time employees to handle the operation

Scenario 7: The manufacturer does not need to bear half the cost of the machine and equipment and does not need to hire additional full-time employees to handle the operation

3 Results and discussion

3.1 Analysis results of each scenario

Based on the two options mentioned above, the study chose "Bamboo waste materials were transported, discarded, and no longer used" and "Bamboo waste was recycled into fuel rods for sale". The former scenario assumed that bamboo waste was discarded and sent to joss paper processing manufacturers for incineration and burial. The manufacturer recycles 218.59×10^{-6} tons/year of bamboo waste, which costs NT$438,000, and calculates the cost-effectiveness after 20 years

(Scenario 1). For the latter scenario, it is assumed that all the bamboo wastes mentioned above were made into fuel rods, and the cost-effectiveness was calculated in scenarios 2 to 7 after 20 years. The analysis results of each scenario are shown as follows:

Scenario 1: The cost-effectiveness of removing and discarding bamboo waste for no longer use

1. Net Present Value Method: The net present value of this situation is NT$-1,110,227, and its value is less than 0; that is, there is no profit to be made, and a high investment cost is needed, so it is not cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is -1, which means not only that there is no profit to be made but also that the investment cost cannot be repaid, so it is not cost-effective.
3. Present Value Cost Method: The present value cost in this scenario is NT$-1,110,227, and its value is greater than 0, which means that the investment cost is higher than the investment income, so it is not cost-effective.
4. Net Annual Value Method: The net annual value of this scenario is NT$-438,000; its value is less than 0, which means there is no income every year, and additional costs are needed, so it is not cost-effective.
5. Annual Cost Method: The annual cost of this scenario is NT$438,000, greater than 0, which means that the annual investment cost is much higher than the income, so it is not cost-effective.
6. Internal Rate of Return Method: There is no internal rate of return in this scenario since its net present value is negative, so there is no internal rate of return to make the net present value zero.
7. External Rate of Return Method: The final value of total revenue in this scenario is negative, which cannot be used as the present value of the total investment in the next period, so there is no external rate of return.
8. Profitability Index Method: The profit index of this scenario is 0, the value is less than 1, and no income can be earned for each dollar of initial investment, so it is not cost-effective.
9. Self-Liquidating Ratio: In this scenario, the self-liquidating ratio is 0, which means there is no income, so it is not cost-effective.
10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is indefinite; that is, the cost cannot be recovered regardless of how many years pass, so it is not cost-effective.

Scenario 2: The manufacturer bears the cost of the equipment and needs to hire additional full-time employees

1. Net Present Value Method: The net present value of this scenario is NT$-5,881,494; its value is less than 0, which means there is no profit to be made, and a high investment cost is needed, so it is not cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is -0.9076; not only is there no profit; but it is also unable to repay the investment cost, so it is not cost-effective.
3. Present Value Cost Method: The present value cost of this scenario is NT$5,881,494, which is greater than 0, indicating that the investment cost is higher than the investment income, so it is not cost-effective.
4. Net Annual Value Method: The net annual value of this scenario is NT$-2,320,331, and its value is less than 0, which means that there is no annual income and additional costs are needed, so it is not cost-effective.
5. Annual Cost Method: The annual cost of this scenario is NT$2,320,331, and the value is greater than 0, meaning that the annual investment cost is much higher than the income, so it is not cost-effective.
6. Internal Rate of Return Method: There is no internal rate of return in this scenario, and since its net present value is negative, there is no internal rate of return to make the net present value zero.
7. External Rate of Return Method: The final total revenue in this scenario is negative and cannot be used as the present value of the total investment in the next period, so there is no external rate of return.
8. Profitability Index Method: The profit index in this scenario is 0.0925, and its value is less than 1, which means that the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
9. Self-Liquidating Ratio: The self-liquidating ratio of this scenario is 0.3046, and the value is less than 1, which means that the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.

10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is indefinite; that is, the cost cannot be recovered regardless of how many years pass, so it is not cost-effective.

Scenario 3: The manufacturer bears the cost of equipment and does not need to hire additional full-time employees

1. Net Present Value Method: The net present value of this scenario is NT$-5,035,653, and its value is less than 0; that is, there is no profit to be made, and a high investment cost is needed, so it is not cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is -0.8936, which means not only is there no profit to be made but also unable to repay the investment cost, so it is not cost-effective.
3. Present Value Cost Method: The present value cost in this scenario is NT$5,035,653, and the value is greater than 0, indicating that the investment cost is higher than the investment income, so it is not cost-effective.
4. Net Annual Value Method: The net annual value of this scenario is NT$-1,986,635, and its value is less than 0, which means that there is no annual income and additional costs are needed, so it is not cost-effective.
5. Annual Cost Method: The annual cost of this scenario is NT$1,986,635, which is greater than 0, meaning that the annual investment cost is much higher than the income, so it is not cost-effective.
6. Internal Rate of Return Method: There is no internal rate of return in this scenario, and since its net present value is negative, there is no internal rate of return to make the net present value zero.
7. External Rate of Return Method: The final value of total revenue in this scenario is negative and cannot be used as the present value of the total investment in the next period, so there is no external rate of return.
8. Profitability Index Method: The profit index in this scenario is 0.1064, and its value is less than 1, which means that the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
9. Self-Liquidating Ratio: The self-liquidating ratio of this scenario is 0.5340, and its value is less than 1; that is, the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is indefinite; that is, the cost cannot be recovered regardless of how many years pass, so it is not cost-effective.

Scenario 4: The manufacturer bears half of the cost of the equipment and does not need to hire additional full-time employees

1. Net Present Value Method: The net present value of this scenario is NT$-3,141,178, and its value is less than 0; that is, there is no profit to be made, and a high investment cost is needed, so it is not cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is -0.8398; that is, there is not only no profit but also an inability to repay the investment cost, so it is not cost-effective.
3. Present Value Cost Method: The present value cost in this scenario is NT$3,141,178, and its value is greater than 0, indicating that the investment cost is higher than the investment income, so it is not cost-effective.
4. Net Annual Value Method: The net annual value of this scenario is NT$-1,239,238, and its value is less than 0; that is, there is no annual income, and additional costs are needed, so it is not cost-effective.
5. Annual Cost Method: The annual cost of this scenario is NT$1,239,238, which is greater than 0, meaning that the annual investment cost is much higher than the income, so it is not cost-effective.
6. Internal Rate of Return Method: There is no internal rate of return in this scenario. Since its net present value is negative, there is no internal rate of return to make the net present value zero.
7. External Rate of Return Method: The final value of total revenue in this scenario is negative and cannot be used as the present value of the total investment in the next period, so there is no external rate of return.
8. Profitability Index Method: The profit index in this scenario is 0.1603, and its value is less than 1, which means that the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
9. Self-Liquidating Ratio: The self-liquidating ratio of this scenario is 0.4039, and its value is less than 1; that is, the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.

10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is indefinite; that is, the cost cannot be recovered regardless of how many years pass, so it is not cost-effective.

Scenario 5: The manufacturer bears half of the cost of the machine and needs to hire additional full-time employees to handle it

1. Net Present Value Method: The net present value of this scenario is NT$-2,295,337, and its value is less than 0; that is, there is no profit to be made, and a high investment cost is needed, so it is not cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is -0.7929; that is, there is not only no profit but also an inability to repay the investment cost, so it is not cost-effective.
3. Present Value Cost Method: The present value cost in this scenario is NT$2,295,337, which is greater than 0, indicating that the investment cost is higher than the investment income, so it is not cost-effective.
4. Net Annual Value Method: The net annual value of this scenario is NT$-905,542, and its value is less than 0; that is, there is no annual income, and additional costs are needed, so it is not cost-effective.
5. Annual Cost Method: The annual cost of this scenario is NT$905,542, which is greater than 0, meaning that the annual investment cost is much higher than the income, so it is not cost-effective.
6. Internal Rate of Return Method: There is no internal rate of return in this scenario. Since its net present value is negative, there is no internal rate of return to make the net present value zero.
7. External Rate of Return Method: The final value of total revenue in this scenario is negative and cannot be used as the present value of the total investment in the next period, so there is no external rate of return.
8. Profitability Index Method: The profit index in this scenario is 0.2071, and its value is less than 1, which means that the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
9. Self-Liquidating Ratio: The self-liquidating ratio of this scenario is 0.9387, and its value is less than 1; that is, the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is indefinite; that is, the cost cannot be recovered regardless of how many years pass, so it is not cost-effective.

Scenario 6: The manufacturer bears half of the cost of the equipment and needs to hire additional full-time employees

1. Net Present Value Method: The net present value of this scenario is NT$-400,863, and its value is less than 0; that is, there is no profit to be made, and a high investment cost is needed, so it is not cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is -0.4009; that is, there is not only no profit but also an inability to repay the investment cost, so it is not cost-effective.
3. Present Value Cost Method: The present value cost in this scenario is NT$400,863, which is greater than 0, indicating that the investment cost is higher than the investment income, so it is not cost-effective.
4. Net Annual Value Method: The net annual value of this scenario is NT$-158,146, and its value is less than 0; that is, there is no annual income, and additional costs are needed, so it is not cost-effective.
5. Annual Cost Method: The annual cost of this scenario is NT$158,146, which is greater than 0, meaning that the annual investment cost is much higher than the income, so it is not cost-effective.
6. Internal Rate of Return Method: There is no internal rate of return in this scenario. Since the net present value is negative, there is no internal rate of return to make the net present value zero.
7. External Rate of Return Method: The final value of total revenue in this scenario is negative and cannot be used as the present value of the total investment in the next period, so there is no external rate of return.
8. Profitability Index Method: The profit index in this scenario is 0.5993, and its value is less than 1, which means that the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.
9. Self-Liquidating Ratio: The self-liquidating ratio of this scenario is 0.5993, and its value is less than 1; that is, the initial investment of each dollar cannot obtain a relative amount of income, so it is not cost-effective.

10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is indefinite; that is, the cost cannot be recovered regardless of how many years pass, so it is not cost-effective.

Scenario 7: The manufacturer does not need to bear half the cost of the equipment and no need to hire additional full-time employees

1. Net Present Value Method: The net present value of this scenario is NT$444,978; its value is greater than 0, so there is profit to be made, and then it is cost-effective.
2. Net Present Value Rate Method: The net present value rate of this scenario is 2.8796, which means that the profit can be earned 2.88 times, so it is cost-effective.
3. Present Value Cost Method: The present value cost in this scenario is NT$-444,978, and the value is less than 0, indicating that the investment cost is lower than the investment income, so it is cost-effective.
4. Net Annual Value Method: The net annual value in this scenario is NT$175,550, and its value is greater than 0; that is, the average annual income is greater than the cost, so it is cost-effective.
5. Annual Cost Method: The annual cost in this scenario is NT$-175,550, which is less than 0, meaning that the annual investment cost is much lower than the income, so it is cost-effective.
6. Internal Rate of Return Method: The internal rate of return in this scenario is 1,000,000%, and its net present value is positive, so the discount rate is within the normal range, and it is profitable.
7. External Rate of Return Method: The external rate of return in this scenario is 0.1038%; that is, when the discount rate is 0.1038%, the earnings are sufficient to cover the cost of the next investment.
8. Profitability Index Method: The profit index in this scenario is 3.8782, and its value is greater than 1, which means that the initial investment of each dollar can obtain nearly 3.9 times the income, so it is cost-effective.
9. Self-Liquidating Ratio: The self-liquidating ratio of this scenario is 0.87823, and its value is greater than 1; that is, each dollar of the initial investment can obtain nearly 3.9 times the income, so it is cost-effective.

10. Dynamic Investment Payback Period: The dynamic investment payback period of this scenario is one year; that is, the cost can be recovered after one year, so it is cost-effective.

3.2. Comparison of Analytical Values for Each Scenario

It can be calculated by the formulas of NPV, NPVI, PC, NAV, AC, IRR, PI, SLR, and T, and the only profitable scenario is if the government bears all the cost of equipment and does not hire a full-time employee. For other scenarios, no matter what formula is used for calculation, they cannot be selected, and the comparison of each scenario is shown in Table 1 below:

Table 1
Cost effectiveness comparison of each scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Criteria
NPV ($/20years)	-1,110,227	-5,881,494	-5,035,653	-3,141,178	-2,295,337	-400,863	444,978	≥ 0
NPVI	-1	-0.9076	-0.8936	-0.8398	-0.7929	-0.4009	2.8796	≥ 0
PC ($/20years)	1,110,227	5,881,494	5,035,653	3,141,178	2,295,337	400,863	-444,978	≤ 0
NAV ($/year)	-438,000	-2,320,331	-1,986,635	-1,239,238	-905,542	-158,146	175,550	≥ 0
AC ($/year)	438,000	2,320,331	1,986,635	1,239,238	905,542	158,146	-175,550	≤ 0
IRR (%)	None	None	None	None	None	None	1,000,000	≥Discount rate
ERR (%)	None	None	None	None	None	None	0.1038	≥Discount rate
PI	0	0.0925	0.1064	0.1603	0.2071	0.5993	3.8782	≥ 1
SLR	0	0.3046	0.5340	0.4039	0.9387	0.5993	3.8782	≥ 1
T (year)	∞	∞	∞	∞	∞	∞	1	The smaller the better

(Source: From this study)

1. NPV

The NPV of each scenario is shown in Fig. 7. In the scenario in which the manufacturer of the fuel rods bears all the equipment costs (Scenarios 2 and 3) and the manufacturer bears half of the equipment costs (Scenarios 4 and 5), the NPV is lower than the NPV of bamboo waste removal (Scenario 1). However, the government that bears all the equipment costs for making fuel rods (Scenarios 6, 7) has a higher NPV than the NPV for bamboo waste removal (Scenario 1). Judging by NPV, scenarios 6 and 7 are better than scenario 1.

2. NPVI

The NPVI of each scenario is shown in Fig. 8. The NPVI of Scenario 2 to Scenario 7 was higher than the NPVI of Scenario 1. The reason is that bamboo waste removal (Scenario 1) only pays the cost of transportation, without any income. In Scenario 2 to Scenario 7, regardless of the total cost, there is income. Therefore, judging by NPVI, the net present value brought by the present value of each unit of investment in Scenario 2 to Scenario 7 is better than that in Scenario 1. However, in Scenario 2 to Scenario 6, the NPVI is less than 0; that is, it is unprofitable.

3. PC

The PC of each scenario is shown in Fig. 9. In the scenarios where the manufacturer of the fuel rods bears all the equipment costs (Scenarios 2 and 3) and the manufacturer bears half of the equipment costs (Scenarios 4 and 5), the PC is higher than the PC of bamboo waste removal (Scenario 1). The government that bears all the equipment costs for making fuel rods

(Scenario 6, 7) has a lower PC than the PC that removes the bamboo waste (Scenario 1); that is, judging by PC, Scenario 6 and 7 are better than Scenario 1.

4. NAV

The NAV of each scenario is shown in Fig. 10. The NAV in these scenarios where the government bears all the equipment costs for making the fuel rods (Scenario 6 and 7) is higher than the NAV of bamboo waste removal (Scenario 1). The NAVs of the other scenarios are much lower than the NAV of Scenario 1.

5. AC

The AC of each scenario is shown in Fig. 11. In the scenarios where the government bears all the equipment costs for making the fuel rods (Scenarios 6 and 7), its AC is lower than that of bamboo waste removal (Scenario 1). In other scenarios, the AC is much higher than the NAV of Scenario 1. However, the AC of Scenario 6 is greater than 0; that is, the annual value of expenses is positive, and the annual expenditure is greater than the income, so the best scenario is still Scenario 7.

6. PI

The PI of each scenario is shown in Fig. 12. Since bamboo waste removal (Scenario 1) only has expenditure but without income, the PI of each scenario is better than the PI of Scenario 1. However, the PI of scenarios 2 to 6 is less than 1, so it is unprofitable, and the selectable project is Scenario 7.

7. SLR

The SLR of each scenario is shown in Fig. 13. Since bamboo waste removal (Scenario 1) only pays for the transportation costs, the PI of each scenario is better than the PI of Scenario 1. The SLR of scenario 1 is less than 0, so this project should not be selected. Only in Scenario 7 is the SLR greater than 1, which means that this project has a fully self-reimbursable ability and is the best choice; the SLR of scenarios 2 to 6 is between 0 and 1, which means that it is not fully self-reimbursable and still needs other financial subsidies.

4 Conclusion

Due to the large amount of bamboo waste materials produced by the production of bamboo sticks, it takes considerable money and manpower to dispose of the bamboo waste materials. Even if it is not removed, the random accumulation of bamboo waste materials can also cause environmental damage. Therefore, this study applies techno-economic analysis and cost-benefit analysis to evaluate the economic value of increasing equipment investment, the value of reusing bamboo waste materials into bamboo fuel pellets (rods), and the feasibility of achieving environmentally sustainable development. The analysis methods are the net present value method, net present value rate method, present value cost method, net annual value method, annual cost method, internal rate of return method, external rate of return method, profitability index method, self-liquidating ratio method, and dynamic investment payback period method to evaluate the benefits of different scenarios. This study results show that to minimize the waste of resources and achieve a balance between environmental protection and socioeconomic benefits when turning bamboo waste materials into fuel pellets (rods), the best project is the scenario where the cost of the equipment is fully borne by the government and no need to hire additional professional employees to monitor the equipment (Scenario 7); in addition, the net present value method, present value cost method, net annual value method, and annual cost method are used to evaluate the scenario in which the costs of the equipment to make the fuel rods were fully borne by the government and a professional employee was hired to monitor the equipment

(Scenario 6) and the scenario in which additional employees were not hired to monitor the equipment (Scenario 7) was better than removing the waste (Scenario 1); if using the net present value rate method, profitability index method and self-liquidating ratio method for evaluation, all scenarios are better than scenario 1, but only scenario 7 is profitable; if evaluated by the internal rate of return method, external rate of return method and dynamic investment payback period method, only scenario 7 is profitable, and others should not be selected. This result can provide a reference for government energy departments to promote the construction of a regional circular economy industrial model for bamboo waste materials and implement a circular economy.

Declarations

We confirm here any of the declarations listed below are "**not applicable**" to the content of our submission.

Ethical Approval

(applicable for both human and/ or animal studies. Ethical committees, Internal Review Boards and guidelines followed must be named. When applicable, additional headings with statements on **consent to participate** and **consent to publish** are also required)

Competing interests

(always applicable and includes interests of a financial or personal nature)

Authors' contributions

(applicable for submissions with multiple authors)

Funding

(details of any funding received)

Availability of data and materials

(a statement on how any datasets used can be accessed)

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Figures

Figure 1

Long-term accumulation of bamboo waste material can cause environmental problems easily.

Source: From this study.

Figure 2

A lot of bamboo waste materials are generated when making bamboo sticks.

Source: From this study.

Figure 3

In the process, the bamboo waste materials are first crushed into uniform materials.

Source: From this study.

Figure 4

Shaped bamboo fuel rods.

Source: From this study.

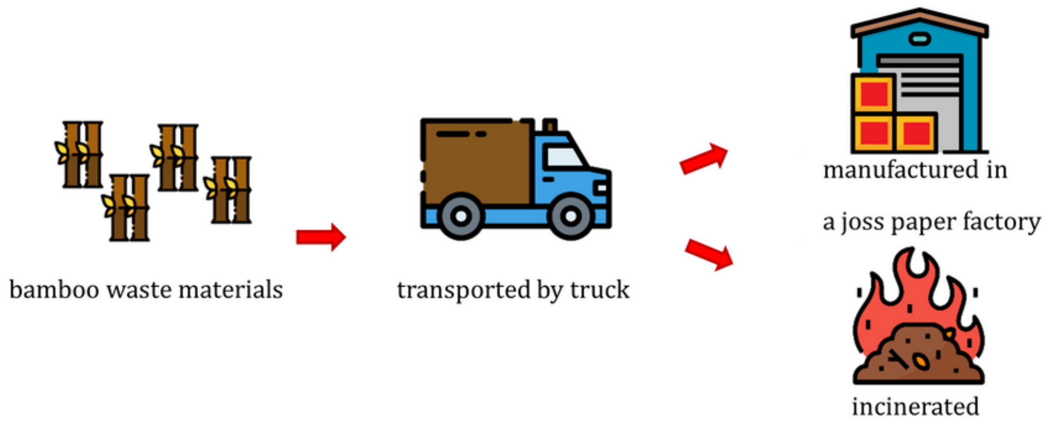

Figure 5

Schematic diagram of the bamboo waste recycling process. (Source: From this study)

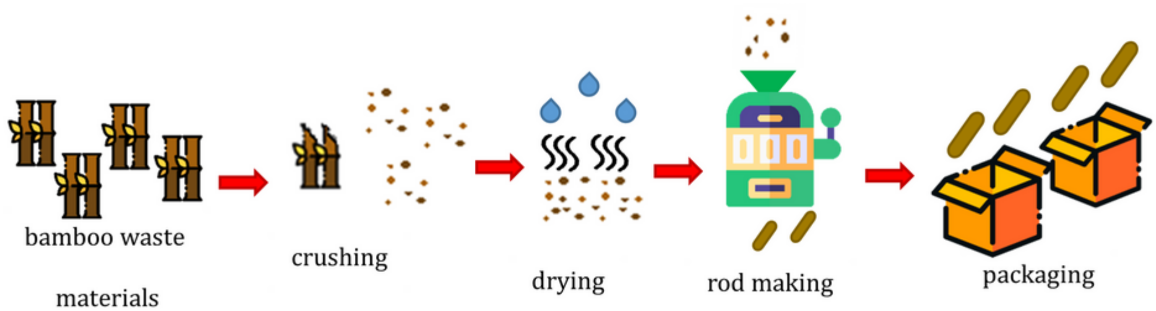

Figure 6

Schematic diagram of the process of making fuel rods from bamboo waste materials (Source: From this study)

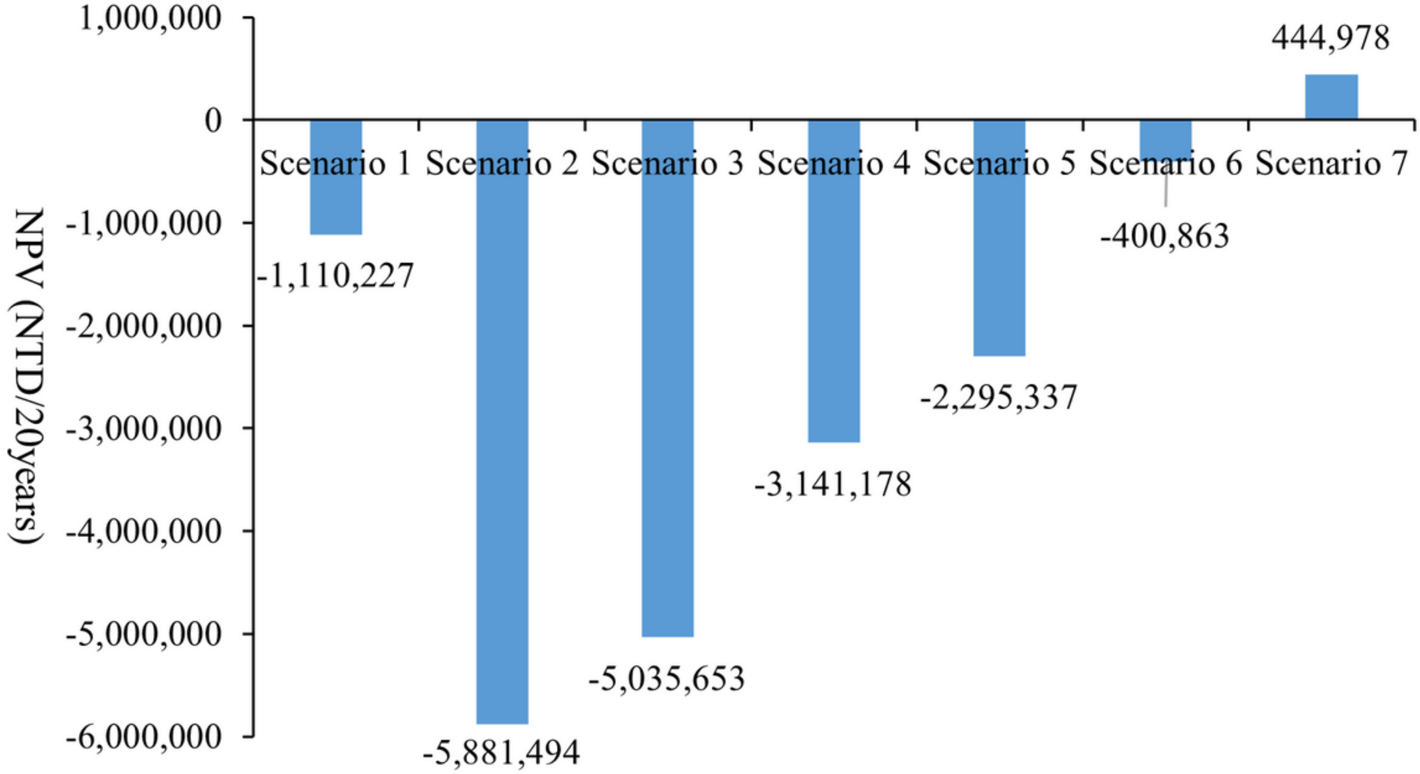

Figure 7

The comparison of NPV in each scenario (Source: From this study)

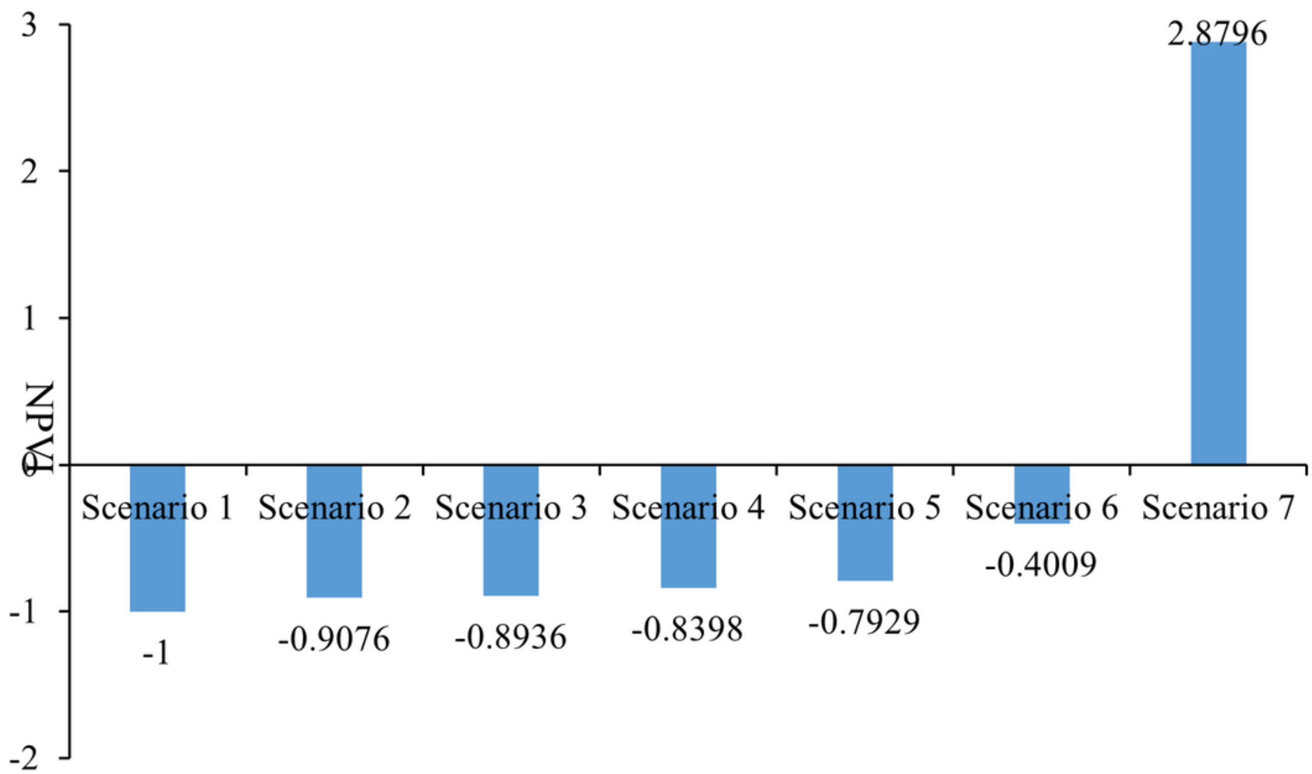

Figure 8

Comparison of NPVI in each scenario (Source: From this study)

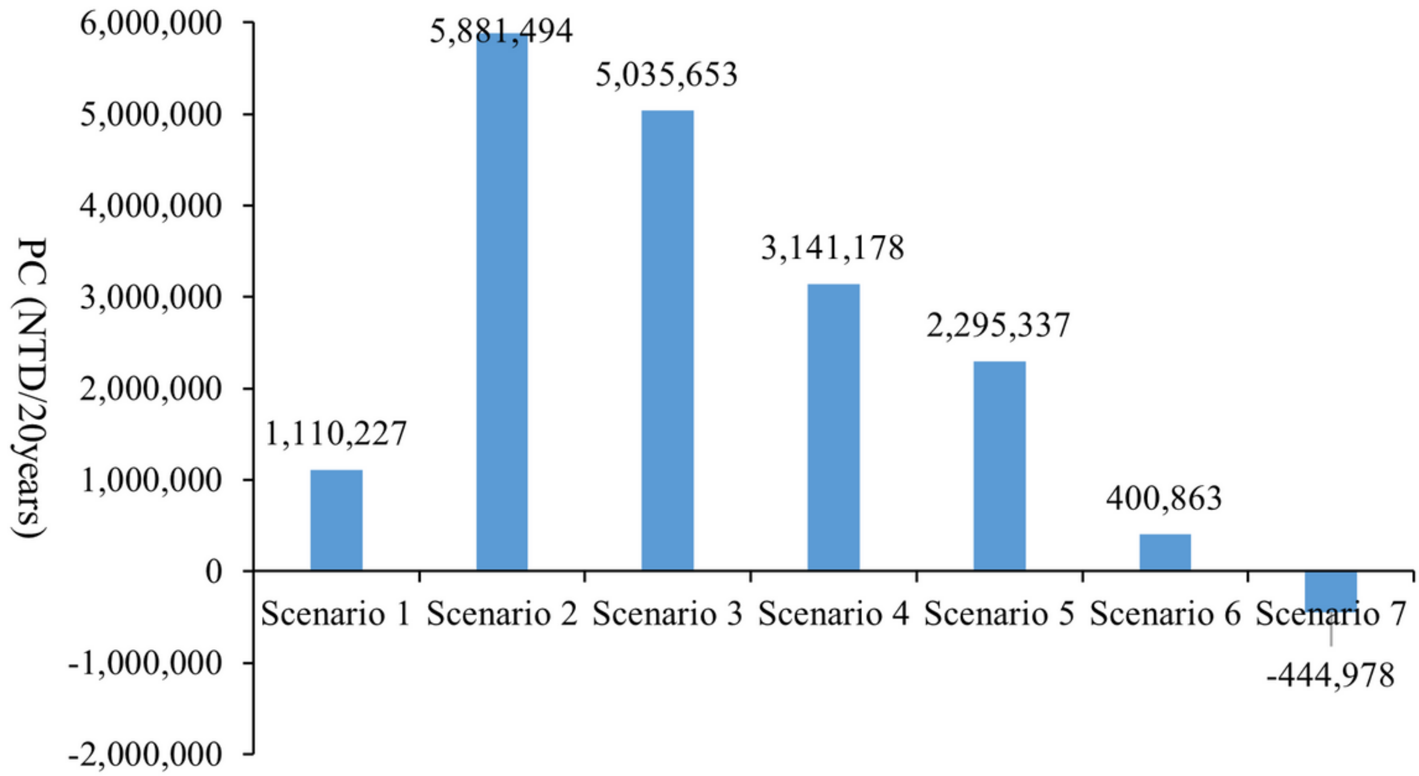

Figure 9

PC comparison in each scenario (Source: From this study)

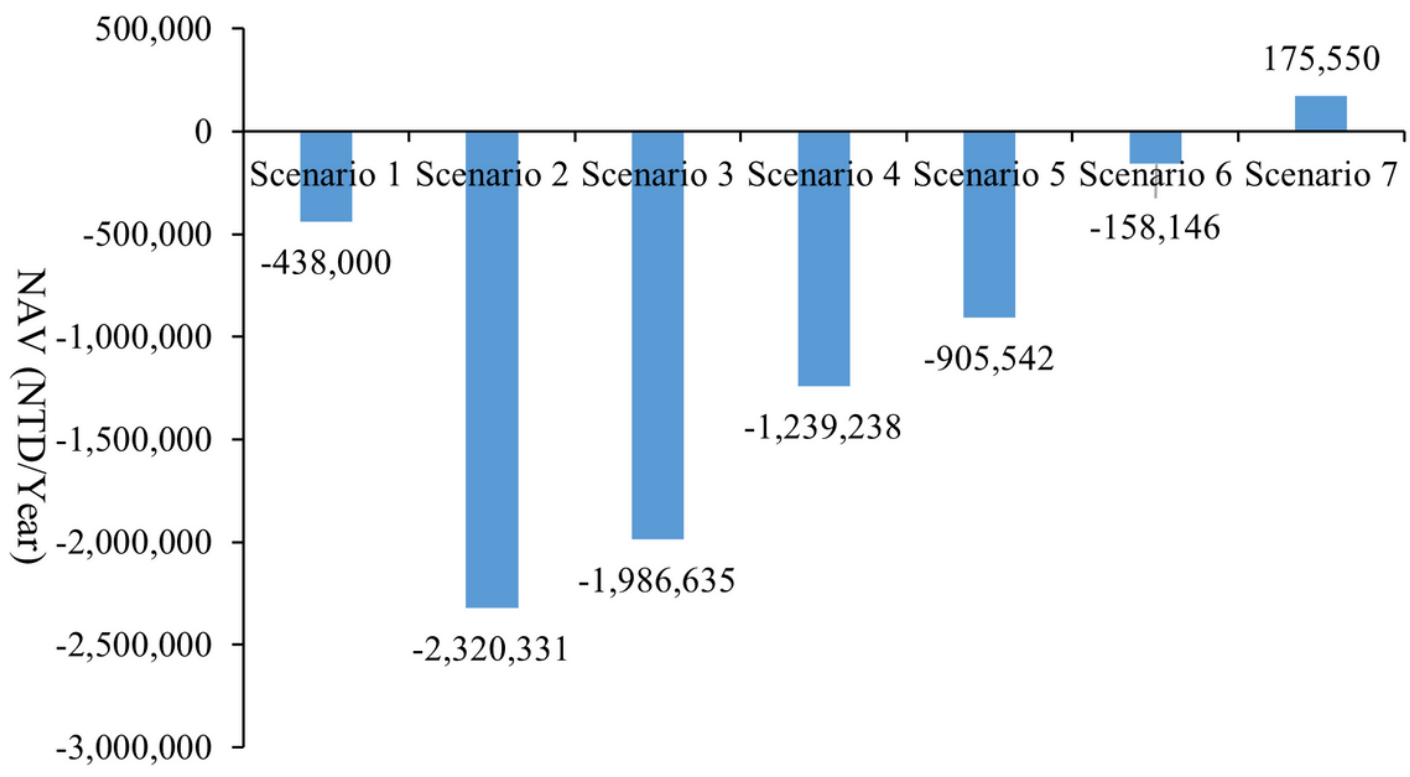

Figure 10

Comparison of NAV in each scenario(Source: From this study)

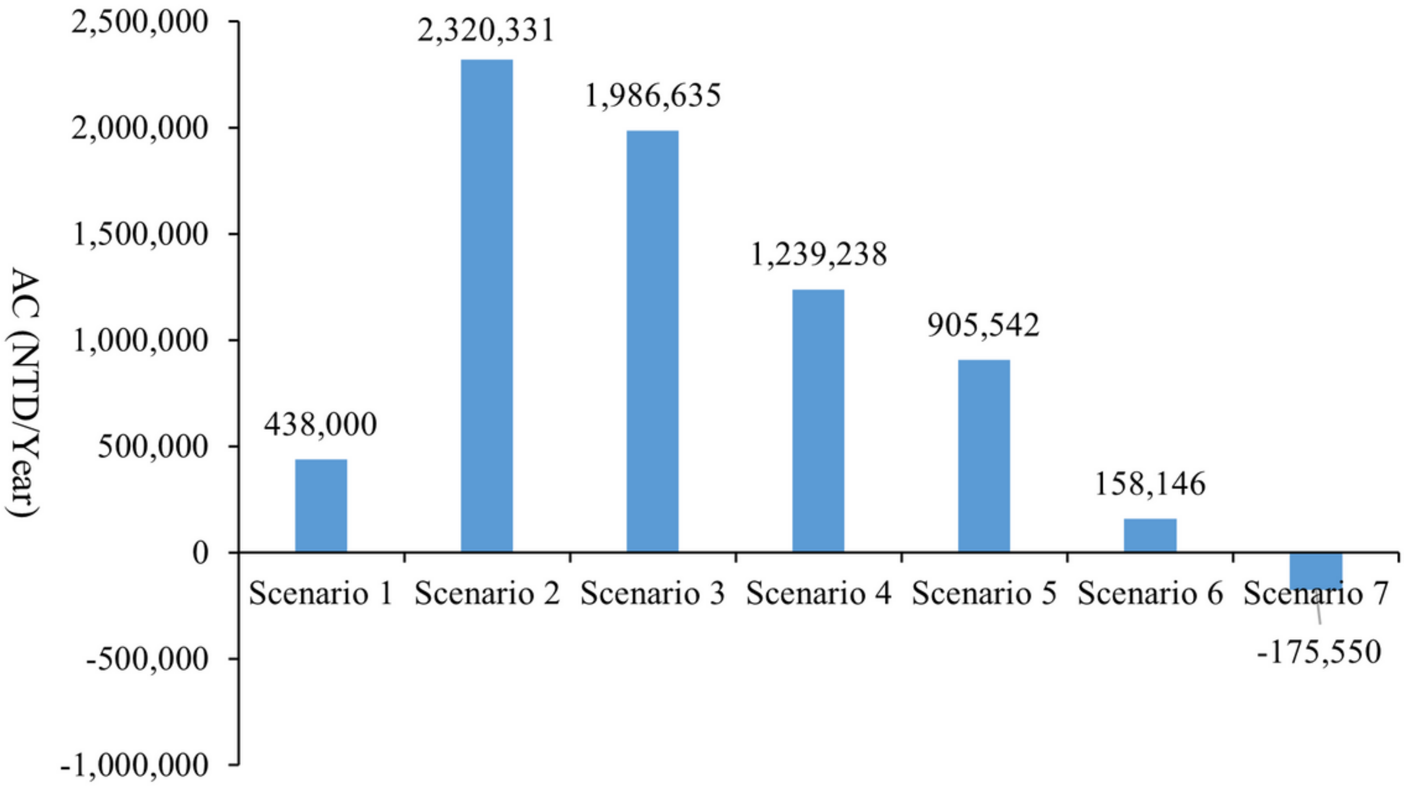

Figure 11

AC comparison of each scenario (Source: From this study)

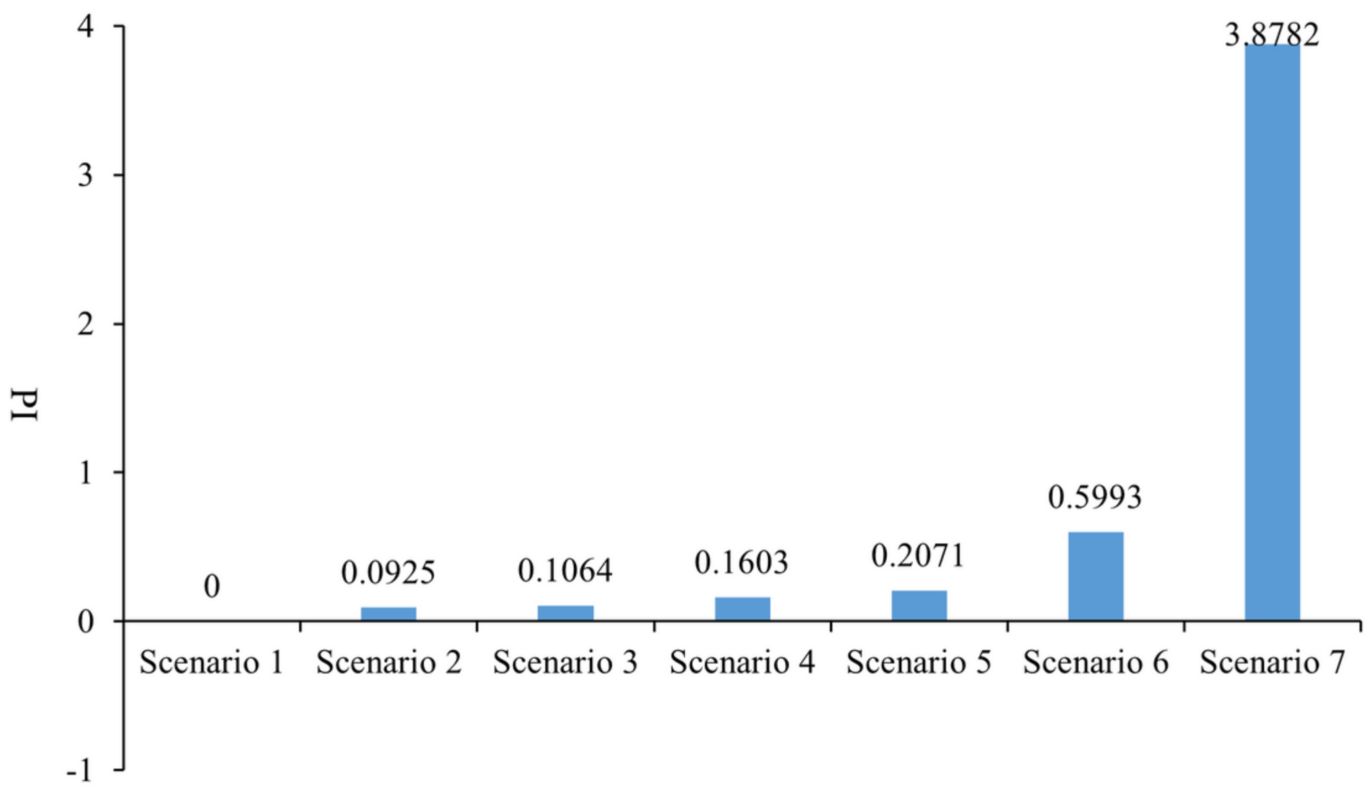

Figure 12

The PI comparison of each scenario (Source data: From this study)

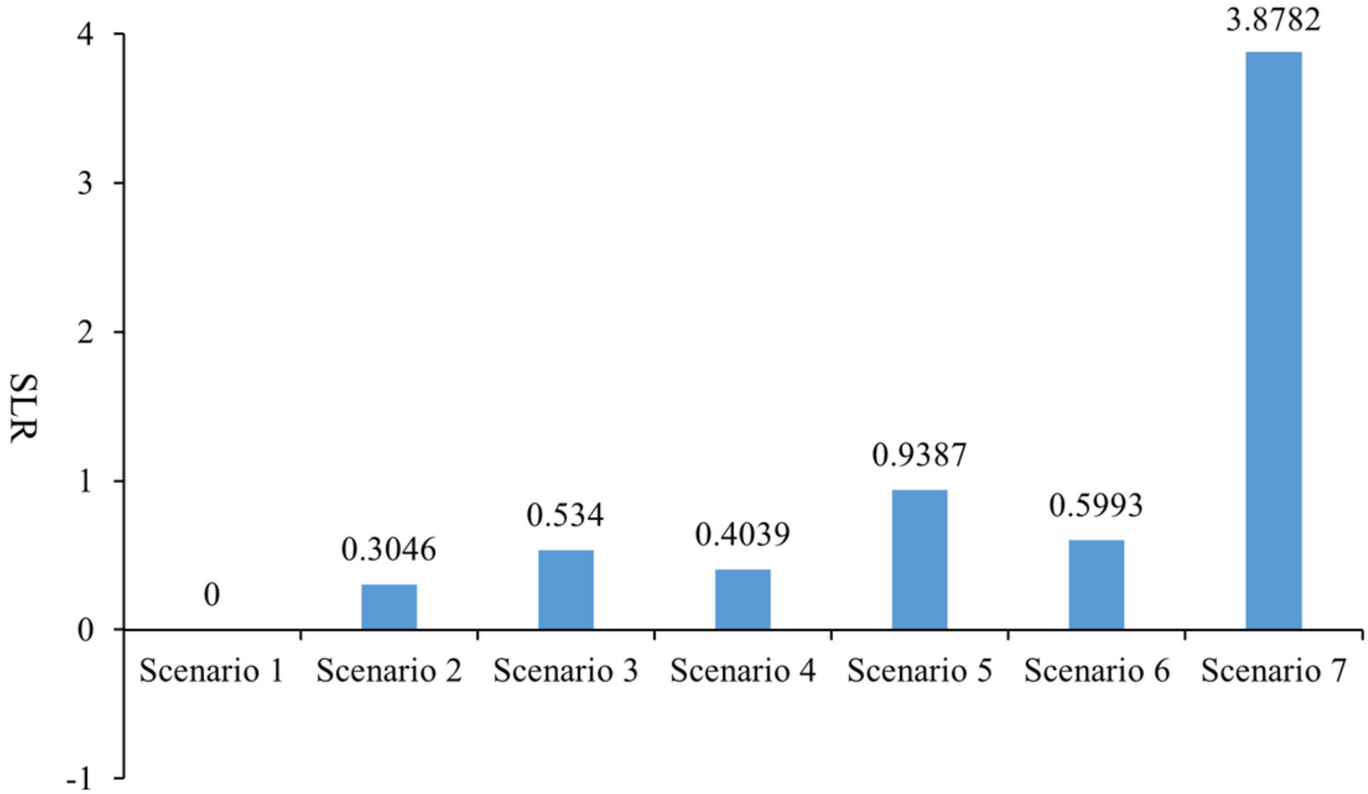

Figure 13

SLR comparison of each scenario (Source: From this study)