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Evaluation of Greenhouse Gas Emissions and Energy Recovery from Planting Street Trees

Chen YC*

Department of Civil Engineering, National Taipei University of Technology, Taipei City, 106, Taiwan (R.O.C.)

***Corresponding author:** Chen YC, Assistant Professor, Department of Civil Engineering, National Taipei University of Technology, Taipei City, 106, Taiwan (R.O.C.), Tel: +886-2-2771-2171#2634, E-mail: ycchen@ntut.edu.tw

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Abstract

Wood is used worldwide for a variety of purposes and its waste products are an attractive low-cost renewable fuel. Previous studies have discussed the cost-effectiveness of planting street trees, focusing on their role in carbon abatement, but have not considered other treatments. This study evaluated street trees' potential for energy recovery and greenhouse gas (GHG) mitigation/emissions throughout their lifespans. Trees can mitigate GHG emissions as a result of CO_2 uptake during growth; but GHGs are emitted when the branches and/or leaves are used as compost or the tree is used as fuel at the end of its life. This study examined the street trees planted over a 41-year period (1976-2017) along the sidewalks of the Tianliao River in Keelong city in Taiwan. The results showed that planting street trees helps to mitigate climate change by reducing total GHG emissions (15,661 ton CO_2-eq) and produces a large amount of renewable energy (5.9×10^6 kWh). The GHG mitigation during the lifespans of street trees can efficiently compensate for the GHG emissions that occur during end-of-life treatment (including incineration and composting). The amount of energy recovered from street trees is positively related to total tree volume. The cost-effectiveness analysis showed that US$223,992 dollars were saved over the study period due to the reduction in carbon tax achieved by the mitigation of GHGs. However, the costs of incinerating wood waste (US$317,490 dollars) were higher than the amount saved by substituting wood waste for coal (US$3,261). The analysis of GHG emissions and economic revenues showed that planting *Ficus microcarpa* resulted in the largest reduction in GHGs (13,484 ton CO_2-eq) and achieved the highest revenues (US$188,068 dollars). The results of this study should increase awareness of the importance of planting trees and managing wood waste to in environmental protection strategies for mitigating climate change.

Keywords: Compost; Cost; Greenhouse Gas; Incineration; Lifespan; Street Tree

Introduction

In recent years, concerns about greenhouse gas (GHG) emissions have led to increased interest in alternative energy production. In Taiwan, 99% of the energy is imported [1], and energy needs account for large amounts of human and natural resources. Biomass is a renewable and cost-effective energy source [2]. Specifically, wood, which is used extensively worldwide, produces waste that is an attractive low-cost source of renewable fuel [3]. From a resource perspective, trees can be divided into large volume parts such as big roots and tree trunks and small volume parts such as branches and leaves. In Denmark, garden waste such as branches, wood, and roots and can be reclassified as fuel and incinerated for energy production. Converting wood from garden waste into a biomass fuel is an attractive option. Home-composting could also be a solution to the problem of the increasing amounts of garden waste [4]. In Taiwan, about 1~2% of municipal solid waste (MSW) is garden waste [5], and most of it is incinerated without further treatment or recycling.

The three major management options for the disposal of wood and the waste it produces are landfilling, recycling, and energy recovery from incineration [6]. Landfilling is the most common option, but it is not suitable in Taiwan due to limited land. Hong Kong and Singapore have the same limitation [6]. Landfilling can be used for the products of the incineration of wood waste, as this greatly reduces the volume of the waste. Recycling wood waste is common in Taiwan. It has the benefit of extending the waste stream, adding some use life before the wood is incinerated or landfilled. The recycling process further delays the release of the carbon dioxide (CO_2) stored in wood [6]. Another benefit of recycling is that it can decrease environmental burdens by reducing the amounts of materials, water, and energy used in the production processes [7,8]. At the macroscopic scale, recycling decreases the frequency of natural disasters related to climate change [9,10].

Wood has been used for cooking and heating since ancient times. It easily produces energy but releases harmful air pollutions such as GHGs and dioxins [11]. One method for estimating the impact of human activities on the environment in terms of GHG emissions is the carbon footprint measurement [12]. Nebel, *et al.* [13] studied the environmental impacts of the production of particleboard and plywood and concluded that the production of wood products efficiently offset the effects of climate change. One study found that heat production based on biomass fuels (woodchips) contributed less to climate change than heat production based on liquefied natural gas (LNG) [14]. Several studies have addressed the energy potential and/or climate impacts of incinerating wood waste at different geographical scales [15]. No studies have compared the impacts of different treatment processes of wood and wood waste on energy recovery and climate change.

In recent years, considerable effort has been devoted to developing waste-to-energy (WTE) technologies that can reduce the volume of waste and mitigate its negative effects on the environment [16]. The average efficiency of WTE plants is about 18% for electricity generation and 63% for heat production when comparing mean output energy divided by input energy [17]. It is cost-effective, with an energy cost of approximately 10% of solar energy and 66% of wind energy [18]. Globally, more than 600 WTE plants incinerate about 181 Mt of MSW each year to generate energy or electricity [19]. Taiwan has 24 WTE plants in operation, and has the highest density of MSW incinerators (number of MSW incinerators/land area) in the world. The power generation capacity of these 24 WTE plants is 558.5 MW [20]. The WTE technology in Taiwan generally converts the energy content of waste into electricity. Studies have evaluated the GHG emissions from waste incineration and demonstrated that waste incineration can serve as a GHG sink—in other words, the production of energy or electricity from waste could mitigate GHG emissions [16]. The MSW in Taiwan is mostly sent to WTE plants for incineration. Among the types of waste, wood has not been properly managed; it has a higher potential for energy recovery and lower climate impacts than other types of waste.

This study evaluated the life-long potential GHG emissions and energy recovery for street trees and their waste. GHGs are emitted when trees are composted or incinerated, but the photosynthesis of living trees mitigates GHG emissions. Incineration can simultaneously produce GHGs and recover energy. The cost-effectiveness of GHG mitigation processes for energy recovery and reducing carbon tax were also calculated in this study. It is known that carbon tax issues associated with climate change are an important international concern [21]. To the best of our knowledge, only one study has considered the cost-effectiveness of planting street trees to reduce atmospheric GHGs [22]. Kovacs, *et al.* [23] discovered that the cost-effectiveness of planting street trees has focused on carbon abatement, but did not consider other services provided by street trees. The results of this study will help to make managers, governments, and the general public more aware of how planting trees and managing wood waste can help to mitigate climate change.

Materials and Methods

System boundaries used in this study

The study area consisted of the sidewalks along the 1.8 km Tianliao river in Keelong city (measured from the port to the Keelong river) (Figure 1). The Tainlaio River is the first artificial canal in Taiwan and plays an important role in surrounding residents' lives, as it is used for exercising, and entertainment. It has not been used for shipping since ancient times. Researchers found that the average lifespan of street trees in this area is 40 years (The Tree Conservation Society of Taiwan, 2014) [24]; therefore, this study evaluated the effects of street trees over a 41-year period, as living trees from 1976 to 2016 and in their end-use (mortality) in 2017.

Figure 1: Research framework

The research framework is shown in Figure 2. Street trees both emit and mitigate GHGs over their lifespans. This study evaluated the GHG mitigation from photosynthesis and the GHG emissions created by the composting of branches and/or leaves during the trees' lifespans. Ounce cut down, most street trees are incinerated in nearby incinerators, creating GHG emissions during the end-use for energy recovery. This study did not consider other recycling treatments that are not common in Taiwan. GHG emissions from seeding, cultivation, maintenance, transportation, electricity usage, and other external factors were also ignored.

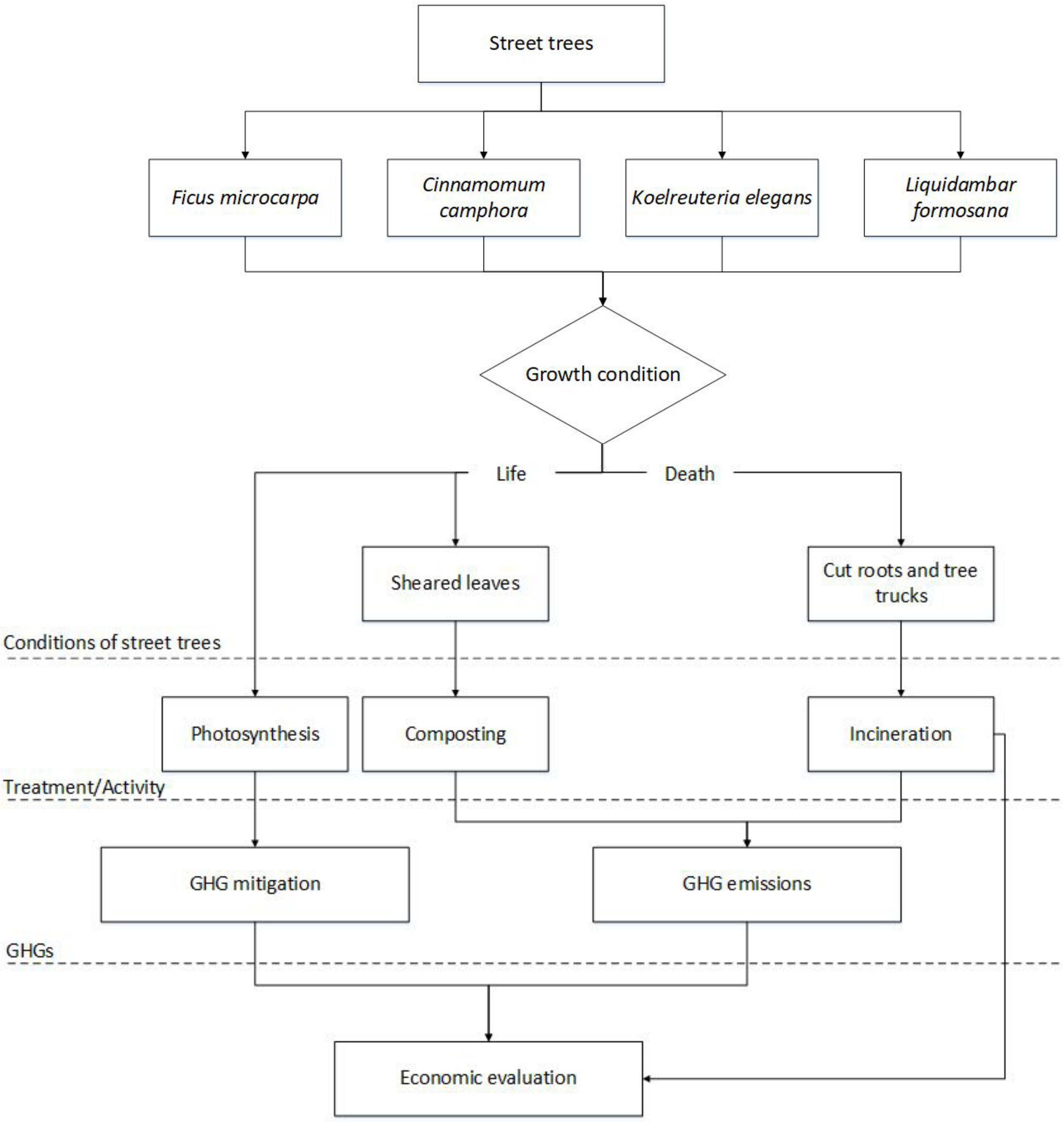

Figure 2: Research framework of this study

Quantification of street trees

This study estimated the number of street trees based on the amount of roads in the area. Therefore, it was calculated as follows:

$$n = \frac{(L_{road} - c_x \times 0.006)}{D_{tree}} \tag{1}$$

where n is the number of street trees planted along sidewalks, L_{road} is the length of roads (km), and c_x is the number of intersections. In addition, D_{tree} is the distance between street trees, which is between 0.005 and 0.010 km depending on the types of street trees (Public Construction Commission, 2018) [25]; 0.006 (km) is the average width of the crossroads in Taiwan.

Street trees' mitigation of GHG emissions

Street trees can mitigate GHGs by carbon fixing. According to the IPCC (2006) [26] guidelines, it can be quantified as follows:

$$GHG_{fix,C} = V \times BD \times BEF \times (1+R) \times CF \times T \text{ and} \tag{2}$$

$$GHG_{fix,CO_2} = GHG_{fix,c} \times 3.67, \quad (3)$$

where $GHG_{fix,C}$ is the volume of carbon fixing and GHG_{fix,CO_2} is the volume of GHG (CO_2) mitigation from a single street tree (ton CO_2-eq). V is the total tree volume (m^3), BD is the average wood density (ton/m^3), which ranges from 0.55 to 0.71 for evergreen broad-leaved trees in Taiwan [27]. BEF is the biomass expansion factor, and it equals 1.20 for evergreen broad-leaved trees [28]. R is the root to shoot ratio, and CF is the carbon fraction. Their averages are 0.234 and 0.4691, respectively, for evergreen broad-leaved trees in Taiwan [29]. T is the lifespan of a street tree, and 3.67 is used to convert CO_2 to C in a chemical formula.

Total tree volume (V) was calculated using Pressler's method, as shown below.

$$V = (BDH/100)^2 \times 0.7853 \times H \times 0.4\ , \quad (4)$$

where BDH is a tree's diameter at breast height (cm), H is the tree height (m), 0.7853 is π/4, and 0.4 is the Pressler average (Taiwan EPA, 2013).

GHG emissions and energy recovery from recycled street trees

Sheared branches (small volume) and/or cut street trees (big volume) can be treated as wood waste. Taiwan's regulations allow trees to be sheared to a maximum of 25% of the total tree volume (V), which balances the trees' health with not allowing trees to affect traffic or pedestrians. Therefore, this study assumes that each year, 25% of the total volume of trees in the area was composted, which generates methane (CH_4). Carbon dioxide emissions can be treated as carbon neutral during the recycling of wood waste [8]. Therefore, the GHG emitted from the composting of sheared branches can be calculated as follows:

$$GHG_{compost} = V \times BD \times GWP \times 25\% \times 3\% \times C_{wood} \times T, \quad (5)$$

where $GHG_{compost}$ is the GHG emissions from composting (ton CO_2-eq). The global warming potential (GWP) of CH_4 is 28 [26]. Methane production from composting averages 3% of the carbon content in wood waste (C_{wood}) [4]. The carbon content in wood waste is about 0.5 kg/kg (Kim and Song, 2014) [8].

Street trees that have been cut down are incinerated for energy recovery. Therefore, their GHG emissions and energy recovery can be calculated as follows:

$$GHG_{incineration} = M \times E \times EF_{el} \times 0.278 \times 10^{-3} \text{ and} \quad (6)$$

$$RE = M \times E \quad (7)$$

where $GHG_{incineration}$ is the GHG emissions from the incineration (ton CO_2-eq), M is the mass of wood (kg), which is converted by multiplying the total tree volume (V) by 1,200, as the average density of street trees in Taiwan is 1,200 kg/m^3 [30]. E is the heating value of wood waste and equals 19.87 MJ/kg (Hossain et al., 2016). EF_{el} is the GHG emission factor for electricity in Taiwan and equals 0.554 kg CO_2-eq/kWh [31]. 0.278 and 10^{-3} are the figures for converting from MJ to kWh and kg to ton, respectively.

Cost-effective analysis

This study considered economic costs (P_{total}, US$) from three perspectives. First, street trees' mitigation of GHG reduces carbon taxes; second, replacing coal in energy-generating incinerators saves money; and third, the fees charged by incinerators. The calculations are shown below:

$$P_{total} = (P_{coal} \times 91\% \times M) + (GHG_{total} \times P_{Carbon}) - (2{,}700 \times M) \text{ and} \quad (8)$$

$$GHG_{total} = GHG_{compost} + GHG_{incineration} - GHG_{fix,CO_2}\ , \quad (9)$$

where P_{total}, P_{coal}, and P_{Carbon} are total price, price of coal, and carbon tax, respectively (calculated in US$). GHG_{total} is the total GHGs emitted during composting, incineration, and CO_2 fixing (ton CO_2-eq). The heating value of wood waste is only 91% that of coal (Hossain et al., 2016). The price to incinerate wood waste as municipal solid waste in Taiwanese WTE plants is NT$2,700/ton (US$90).

Results and Discussions

Quantification of street trees

The Tianliao River in Keelong city was the first artificial canal used to import products into Taiwan. It is 1.8 km long (from the port to the Keelong River) and is crossed by 11 roads. The four most common trees planted along the Tianliao River are *Ficus microcarpa*, *Liquidambar formosana*, *Cinnamomum camphora*, and *Koelreuteria elegans* due to geophysical and climatic conditions. Specifically, 34% and 30% of the trees are *Ficus microcarpa* and *Cinnamomum camphora*, followed by *Koelreuteria elegans* (13%) and *Liquidambar formosana* (9%). These trees are representative of the types of trees planted throughout Taiwan. Other types of street trees that made up less than 5% of total street trees in the study area were ignored in this study. In New York, the London plane tree (*Platanus acerifolia*), callery pear (*Pyrus calleryana*), kwanzan cherry (*Prunus serrulata*), and eastern white pine (*Pinus* *strobus*) are the representative street trees [23]. Representative street trees are vary across countries and the evaluation methods presented in this study can be applied worldwide.

According to the formula for quantifying trees given above, there were 366 street trees in the study area. However, an in-situ survey found 390 street trees, an increase of about 7% over the estimate. This bias may be caused by the varying widths of the cross roads. The in-situ average distance between street trees was 0.008 km, but the distance between the trees depended on the type of trees. For example, the recommended distances between trees are 0.005~0.006 km and 0.006~0.007 km for *Koelreuteria elegans* and *Cinnamomum camphora*, respectively [29]. The formula given above would be reasonable (<10% bias) for quantifying street trees in areas too large to survey or when the numbers cannot be easily collected in-situ.

GHG mitigation and emissions from street trees

Trees store GHG as a result of CO_2 uptake during their growth [23,32]. However, GHGs may be emitted when the branches and/or leaves of street trees are sheared off and used as compost or fuels (Figure 2). As shown in Figure 3, a maximum of 13,484 tons of CO_2-eq GHGs are absorbed by *Ficus microcarpa* during its lifespan. The *Cinnamomum camphora* and *Liquidambar formosana* absorb 1,567 and 454 tons CO_2-eq GHGs, respectively. A *Koelreuteria elegans* mitigates a minimum of 370 ton CO_2-eq GHGs. In this study, a single *Ficus microcarpa* or *Cinnamomum camphora* tree can mitigate 102.9 and 13.5 tons CO_2-eq GHGs, respectively. Both efficiently mitigate GHGs during their lifespans. The stored CO_2 can be in the form of soil organic matter or as tree biomass [33]. In the U.S., more than half of the urban carbon storage is attributed to soils, 20% to vegetation, 10% to forests (trees), 11% to landfills, and 5% to buildings [34]. CO_2 is slowly removed from the atmosphere over long periods of time, and trees' ability to capture and store GHG from the atmosphere plays an important role in climate change mitigation [8]. The trees in this study absorbed a total of 15,875 tons CO_2-eq GHGs, demonstrating that street trees are one of the carbon pools of urban vegetation [35].

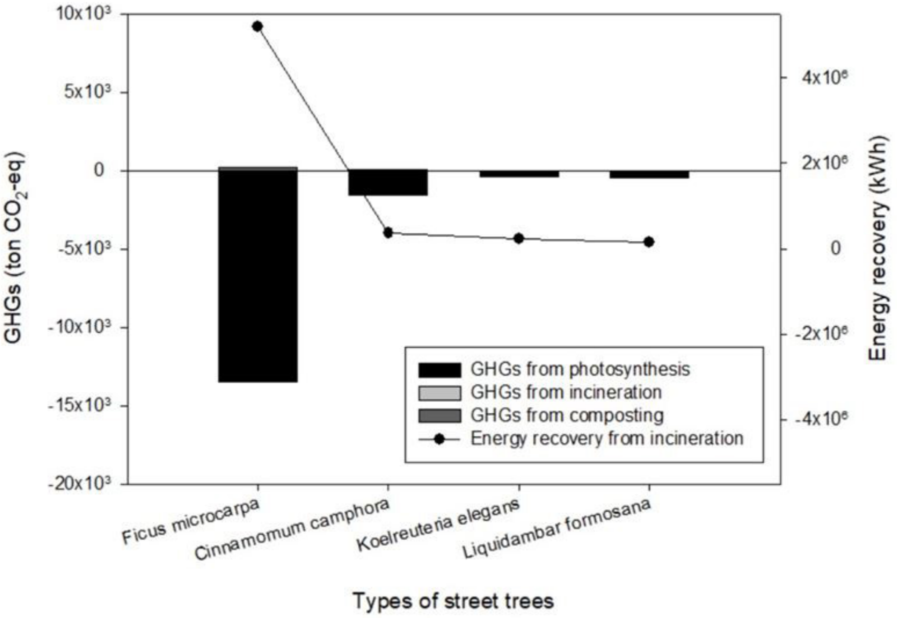

Figure 3: GHG emissions and mitigation from different types of street trees

The total volume of trees examined in this study is shown in Table 1. *Ficus microcarpa* made up the biggest volume (1,835 m^3), followed by *Cinnamomum camphora* (207 m^3), and *Liquidambar formosana* (174 m^3). Therefore, branches and/or leaves sheared each year from *Ficus microcarpa* account for the most GHG emissions from composting (180.6 tons CO_2-eq) (Figure 3). The branches sheared from the *Cinnamomum camphora, Koelreuteria elegans*, and *Liquidambar formosana* emitted 15.0, 8.2, and 6.9 tons CO_2-eq during composting, respectively. Together, composting trees emitted 210.7 tons CO_2-eq of GHGs over the study period. This study established that the amount of GHG emissions from composting can be estimated from the total volume of the existing street trees.

Species of street tree	BDH (m)	H (m)	Canopy area (m)	Height of lowest-branch (m)
Ficus microcarpa	67.2	11.5	18.5	2.1
Cinnamomum camphora	18.7	4.8	8.5	1.8
Koelreuteria elegans	26.4	7.0	8.9	2.0
Liquidambar formosana	25.3	7.7	6.6	2.4

Table 1: Total volume of different types of street trees (Taiwan EPA, 2013)

Once cut down, street trees in Taiwan are frequently incinerated for energy recovery. In the European Union, most wood waste is incinerated for energy recovery [36]. High energy wood waste can replace coal as an attractive source of energy for large-scale biomass incineration plants [3]. In this study, the incineration of *Ficus microcarpa* waste emitted the most GHGs (2.87 ton CO_2-eq), followed by *Cinnamomum camphora* waste (0.21 ton CO_2-eq), *Koelreuteria elegans* waste (0.13 ton CO_2-eq), and *Liquidambar formosana* waste (0.08 ton CO_2-eq) (Figure 3). A total of 3.29 tons CO_2-eq GHGs were emitted during the incineration of this waste, which was 65 times lower than the total GHG emissions from composting.

During our study period, the incineration process recovered 5.9×10^6 kWh of energy from the street trees: 87% of the energy was from *Ficus microcarpa,* 6.2% from *Cinnamomum camphora*, 3.9% from *Koelreuteria elegans*, and 2.9% *Liquidambar formosana* (Figure 3). Energy recovered from wood waste represents 9% of the bioenergy production in Switzerland [37] and is a substitute for 116 megatons of CO_2-eq/yr from fossil energy [38]. The amount of energy recovered from street trees is mainly dependent on the volume of trees. Studies have found that it requires more energy to incinerate fresh wood than to incinerate old wood because the former has higher moisture content [8]. McPherson and Simpson [39] also found that potential energy recovery depends on the size of the tree.

In sum, incinerating and composting the wood waste from street trees generated 3.29 and 210.7 tons of CO_2-eq, respectively; however, the trees' carbon fixing mitigated GHG 15,875 tons of CO_2-eq over the lifespans of street trees. Thus, the amount of GHG absorbed by street trees was much higher than the GHG emissions created by both composting and incineration. It is important to note that although recycling wood waste, especially through composting, produces GHGs, street trees can mitigate climate change by absorbing 15,661 tons of CO_2-eq from the atmosphere and can produce great amounts of renewable energy (5.9×10^6 kWh). These results suggest that planting street trees should be encouraged.

Cost-effectiveness of street trees

This study also considered the cost-effectiveness of street trees for GHG mitigation; it considered the reduction in the carbon tax, the use of wood waste to replace coal in energy-generating incinerators, and the fees charged by incinerators to incinerate wood waste. As shown in Table 2, this study calculated that street trees saved the city US$223,992 dollars: the reduction in carbon tax was US$317,490 dollars, but incinerating wood waste cost US$96,759 dollars and the revenues from replacing coal were only US$3,261 (1% of the incinerating fees). Thus, incinerating wood waste was not a cost-effective treatment. The cost-effectiveness of planting street trees for GHG mitigation varied across different types of trees. *Ficus microcarpa* produced the highest revenue, US$188,068 dollars, followed by *Cinnamomum camphora* (US$25,497 dollars). Both *Liquidambar formosana* and *Koelreuteria elegans* had lower revenues ranging from US$3,762 to 6,665 dollars. The variation in the cost-effectiveness of street trees for abating carbon is attributable to longevity and mature tree size [23]. These data have not been considered in many previous studies, but have economic significance. Expenditures for the planting, pruning, and removal of street trees are high [23] and future studies should include them. Also, the co-benefits of planting street trees in urban areas are substantial, such as reducing air pollution and controlling storm water runoff [40-42].

Street tree	Reduced carbon tax from GHG mitigation (US$)	Revenue from replacing coal in incinerators (US$)	Fees to incinerate wood waste (US$)	Total revenue (US$)
Ficus microcarpa	269,672	2,846	-84,450	188,068
Cinnamomum camphora	31,335	204	-6,042	25,497
Koelreuteria elegans	7,404	127	-3,769	3,762
Liquidambar formosana	9,079	84	-2,498	6,665
Total	317,490	3,261	-96,759	223,992

Table 2: Environmental costs of different street trees

Conclusions

Wood is used extensively worldwide in multiple applications and wood waste is an attractive low-cost source of renewable fuel. This study evaluated the potential for energy recovery and GHG mitigation of street trees and their waste over their entire lifespans. GHGs are emitted during the composting of branches and leaves and during the incineration of roots and tree trunks. However, GHGs are mitigated by photosynthesis during the trees' lifespans. This study examined the balance between these processes over the 41-year lifespans of the street trees planted along the sidewalks of the Tianliao River in Keelong city. The results showed that planting street trees helped to mitigate climate change (15,661 ton CO_2-eq) and produced a great amount of renewable energy (5.9×10^6 kWh). In particular, GHG emissions from incinerating and composting wood waste were 3.29 and 210.7 tons CO_2-eq, respectively. GHG mitigation during the lifespans of street trees efficiently compensates for the GHG emissions during end-of-life treatments (including incineration and composting). The volume of energy recovery and the cost-effectiveness of the GHG strategies were positively related to the total tree volume. Over the study period, US$223,992 dollars were saved by reducing the carbon tax through GHG mitigation. However, the charges for incinerating wood waste (US$317,490 dollars) were much higher than the amount saved by replacing coal with wood waste (US$3,261). The analysis of GHG emissions and economic revenues showed that planting *Ficus microcarpa* efficiently mitigated the highest GHGs (13,484 ton CO_2-eq) and achieved the highest revenues (US$188,068 dollars). These results will raise awareness of the importance of planting trees and managing wood waste in environmental protection strategies to mitigate climate change. Larger geographical scales could be studied in future studies.

Acknowledgments

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