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# Policy Analysis of Biomass Recycling Supply Chain Considering Carbon and Pollution Emission Reduction—Taking China's Straw Subsidy Policy for Example

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**Abstract:** In recent years, global environmental problems such as air pollution and the greenhouse effect have become more and more serious. The utilization of biomass energy not only can promote low-carbon transformation to establish a competitive advantage through value creation under the goals of carbon peaking and carbon neutrality but is also an important force in solving environmental problems. Government subsidy policies play an important role in promoting the development of biomass energy utilization. Taking straw as an example, this paper constructs a straw recycling supply chain system dynamics model consisting of farmers, acquisition stations, power plants, and pyrolysis plants based on a real-world case. Two types of straw processing, namely power generation and pyrolysis, are considered in the model. This paper analyzes the economic and environmental impacts of three subsidy policies, namely the unified rate policy, the linear growth policy, and a two-step policy, by comparing the profit, carbon, and pollution emission reduction benefits of the supply chain under different subsidy scenarios. The result shows that, among the three subsidy policies, the unified rate policy shows the best-promoting effect. The research results and policy implications in this paper could be a reference for governments trying to formulate subsidy policies for developing biomass energy utilization.

**Keywords:** biomass recycling supply chain; government subsidy policies; system dynamics modeling; carbon emission reduction; pollution emission reduction

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## 1. Introduction

As an important basis for human survival and development, fossil energy has supported the development of industrial civilization. But the utilization of this kind of energy has been simultaneously causing serious atmospheric pollution and the greenhouse effect. To cope with increasingly serious environmental problems, the international community reached a consensus on the low-carbon transformation of the energy system [1]. Biomass energy is the fourth largest energy source after coal, oil, and natural gas [2]. The widespread use of biomass energy can not only help to reduce the dependence on nonrenewable fuels, but it can also serve as cheaper, renewable, and greener raw materials in many industries [3,4]. It is valued by countries around the world because it is environment-friendly and conducive to sustainable development. In 2021, China invested CNY 2.5 billion in subsidies for the construction of its biomass energy industry to promote the high-quality development of its national biomass power generation industry [5]. In 2022, the European Commission released an energy transition action plan named REPowerEU, planning to invest EUR 300 billion by 2030 to accelerate the clean energy transition, including biomass energy [6]. Biomass energy has been commonly adopted around the world to cope with climate change, manage environmental pollution, and promote energy transition and green development.

In many agricultural production countries, including China, straw is an abundant biomass resource. Since 2010, China's annual production of straw has exceeded 800 million tons [7], accounting for about 20% of the global annual straw yield [8]. The demand for crop straw processing is high. Improper processing technology might cause serious environmental pollution and a large amount of waste. With the continuous evolution of sustainable development goals and increasingly scarce fossil energy resources, China's energy structure transformation is imminent. The Chinese government has made many efforts to comprehensively utilize straw for the development of energy conservation and emission reduction. By 2021, the comprehensive utilization rate of crop straw in China had reached 88.1% [9]. The capacity for comprehensive straw utilization has been steadily increasing.

Among the various straw resource utilization methods, due to the government's preference to persuade farmers to adopt more environmentally friendly farming practices [10], straw return is still the most common way to deal with straw in most countries, such as the UK, the United States, Canada, and Japan. However, the utilization of straw energy has also been strongly promoted and supported by many developed countries [11]. The reason is that, on the one hand, it can avoid some negative effects on the environment caused by straw return, such as the occurrence of diseases and pests caused by the excessive amount of straw that cannot be naturally decomposed or the soluble organics produced during straw decomposition that will cause water pollution [12]. On the other hand, it can effectively increase the energy supply of the agricultural industry, reduce the waste of resources, and alleviate the contradiction between the supply and demand of fossil energy.

Among the various ways of comprehensive straw utilization in China, the utilization rate of feed and fertilizer is as high as 76.9%, while the utilization rate of energy is only 8.9% [10]. In practice, the large-scale development of the straw recycling supply chain is still hampered by obstacles from both the supply and demand sides. On the supply side, some farmers still dispose of straw by direct incineration [13], which harms the environment. This is not only not in line with the construction task of building a resource-saving and environment-friendly society but also contrary to the strategic goal of sustainable development in China. On the demand side, enterprises' profits could not match the investment in straw recycling [14], which leads to serious impediments to enterprise operation. Many countries chose to grant government subsidies to promote the utilization rate of straw energy [15,16]. But the problem is: what kind of subsidy policy can better promote the utilization of straw energy?

In the current environment of carbon peaking and carbon neutrality goals and the energy crisis, it is a matter of concern for all countries to promote the development of biomass energy utilization through subsidy policies. This paper aims to analyze the effectiveness of government subsidies in promoting biomass energy utilization and try to find the most economically and environmentally beneficial subsidy policy for the supply chain system.

Based on an investigation and interview with a biomass energy company in a northern province of China, this paper constructs a straw recycling supply chain model consisting of farmers, acquisition stations, power plants, and pyrolysis plants. Two commonly adopted straw energy utilization technologies are considered in this research, namely power generation and pyrolysis. In consideration of the government subsidy policy of carbon reduction and pollution reduction, the authors use the system dynamics approach, which could contribute to a better understanding of the influence of a set of factors on the supply chain system, to simulate and analyze the economic and environmental benefits of the straw recycling supply chain under different government subsidy policy scenarios.

Exploring the optimal subsidy policy is a significant issue for enhancing the stickiness of straw recycling enterprises and promoting sustainable economic and environmental development. The main contribution of this paper lies in providing a theoretical reference for government departments to formulate optimal subsidy policies that can promote the energy utilization of straw. In this study, we analyzed how government subsidies could promote straw energy utilization. The result of the simulation indicates that straw power generation or more environmentally friendly methods, such as pyrolysis, can enhance the willingness of farmers to sell and enterprises' recycling, and finally promote environmental protection and green development.

The study consists of the following sections. A literature review is presented in Section 2. The next section is for the main methodology and the system dynamics model. The simulation results of the paper are presented in Section 4. Lastly, Section 5 provides the conclusion and recommendations.

## 2. Literature Review

Scholars have conducted research on energy supply chains from the perspectives of fossil energy supply chains such as coal [17], green supply chains [18], renewable energy supply chains [19], and waste heat recovery energy supply chains [20]. As the concept of a "green supply chain" has gained increasing attention in the pursuit of sustainable development by enterprises globally, leading to the optimization of supply chain management [21,22].

As the fourth largest energy source, biomass energy is becoming increasingly important in the energy system and has gradually become an important part of the energy decarbonization strategy of many countries [23]. With the continuous evolution of sustainable development goals and low-carbon development goals, research on biomass energy supply chains has also flourished in recent years [24]. As a promising renewable energy source, biomass is currently utilized mainly for power generation and pyrolysis [25]. In terms of power generation, the cost of biomass power generation is much lower than the cost of other renewable energy sources and has the advantage of being renewable and sustainable compared to other fossil energy sources, such as coal [26]. The use of biomass for power generation can be traced back to the 1970s, i.e., after the first world energy crisis, when Denmark actively developed renewable energy and first used straw for power generation [27]. In recent years, with the increase in low-carbon and environmental awareness, biomass power generation has received more and more attention from scholars in various countries. Most studies focused on the development potential of biomass power generation, mainly including feasibility studies [28], economic studies [29], and emission reduction potential [30]. In terms of pyrolysis, biomass pyrolysis can effectively improve biomass energy transformation with low environmental impact and has very promising development potential [31]. Existing studies on biomass pyrolysis had mainly studied straw [32,33] and other biomass energy sources [34] from a technical perspective, most of which ignored the social value of pyrolysis plants as a member of the biomass supply chain. One of the contributions of this paper is to consider both power plants and pyrolysis plants as participants in the biomass supply chain and to study their effects on the benefits of the supply chain system.

However, in the energy supply chain industry, biomass recycling enterprises, such as power plants and pyrolysis plants, are facing high costs in various aspects, namely raw material procurement [35], transportation [36], and business operation [37]. The gap between cost and profit has become a key obstacle limiting the large-scale development of biomass recycling enterprises [14]. Countries around the world are actively studying the corresponding incentive systems to promote the development of biomass energy utilization, such as tax incentives [38], investment incentives [39], and green subsidies [40,41]. Although green subsidies can effectively reduce carbon emissions and promote the development of the biomass energy utilization industry to a certain extent, their scope of application is broad and not only applicable to biomass energy utilization enterprises. Therefore, this paper selects subsidy policies that directly affect the supply chain of biomass energy utilization for research. China also attached great importance to the role of incentive systems in promoting the use of biomass for energy. Most of the studies on incentive systems by Chinese scholars have focused on government subsidies. For example, Jiang et al. studied the optimal subsidy strategy when the government subsidizes each of the three members by constructing a biomass supply chain model consisting of farmers, villagers' committees, and power plants [42]. Li et al. compared the effects of the harvesting subsidy policy and the transportation subsidy policy on biomass supply chain members in China [43]. Liu et al. analyzed different combinations of emission trading systems and investment subsidies and simulated the development trend of biomass power generation [14]. Cai et al. found that the amount of government subsidies was positively correlated with the amount of biomass feedstock, but excessive subsidies might harm the reliability of the biomass supply chain [44]. Yang et al. analyzed the impact of China's energy tax subsidy policy on the development of the biomass fuel industry [45]. Li et al. concluded that raw material costs put a lot of pressure on the use of power plants and that electricity price subsidies can help reduce the negative impact caused by high raw material costs [46]. In the study of China's subsidies for the biomass supply chain, previous studies tended to compare the impact of subsidies on the biomass energy supply chain with or without subsidies and paid less attention to how to optimize the subsidies to achieve better results. On this basis, this paper refers to existing studies [14,47] and proposes three government subsidy policies: unified rate policy, linear growth policy, and two-step policy to study the biomass energy supply chain.

Straw production has strong seasonal characteristics [48]. Due to the vast size of China, different types of crops are grown, and harvesting times differ in different regions. Straw is available in all seasons of the year, but there are significant differences in the amount of supply. Overall, China's straw production is highest in September–October, accounting for more than 50% of the annual straw production, and lowest in January–April [49]. Clearly, the straw yield is constantly changing over the seasons, yet little attention has been paid to seasonal differences in straw supply in previous relevant studies.

In the current environment of carbon peaking and carbon neutrality goals and the energy crisis, it is a matter of concern for all countries to promote the development of biomass energy utilization through subsidy policies. The aim of this paper is to analyze the effectiveness of government subsidies in promoting biomass energy utilization and try to find the most economically and environmentally beneficial subsidy policy for the supply chain system. The system dynamics approach is able to show the long-term, dynamic changes and trends of each link of the supply chain from a system perspective with limited data. This approach has advantages in explaining the internal dynamic structure and feedback mechanisms of complex systems. Therefore, it is widely used in supply chain system modeling, such as electronic product supply chain systems [50], automotive supply chain systems [51], construction supply chain systems [52], food supply chain systems [53], pharmaceutical supply chain systems [54], etc. Similarly, it has also been widely used in modeling energy supply chain systems [55–57]. However, few studies on government subsidy policies for the biomass supply chain have used the system dynamics approach, but the wide application of system dynamics methods in energy supply chain modeling again shows the merits and feasibility of the approach. This study might provide a new research perspective for research in this field.

Table 1 compares the most related studies with our work. Obviously, the problem of how the straw recycling supply chain system benefits from using the system dynamics approach has not been thoroughly studied. In this paper, we studied it, considered both power plants and pyrolysis plants as components of the straw recycling supply chain, and analyzed the economic and environmental benefits under different subsidy policies.

**Table 1.** A summary of the most related studies.

| Author [num] | Supply Chain | Biomass Power Generation | Biomass Pyrolysis | Government Subsidy | Method |
|---|---|---|---|---|---|
| Liu et al. [14] | No | Yes | No | Yes | System dynamics model |
| Ribeiro et al. [28] | No | Yes | No | No | Evaluate |
| Daiem et al. [29] | No | Yes | No | No | Evaluate |
| Yao et al. [30] | No | Yes | No | No | Grey prediction model and scenario analysis |
| Sui et al. [32] | No | No | Yes | No | Experiment |
| Sun et al. [33] | No | No | Yes | No | Experiment |
| Jiang et al. [42] | Yes | Yes | No | Yes | Stackelberg game |
| Li et al. [43] | Yes | No | No | Yes | Stackelberg game |
| Cai et al. [44] | Yes | No | No | Yes | Evaluate |
| Yang et al. [45] | No | No | No | Yes | Partial equilibrium model |
| Li et al. [46] | No | Yes | No | Yes | Game-theoretic |
| Liu et al. [47] | Yes | Yes | No | Yes | Multi-objective optimization and system dynamics model |
| Saavedra et al. [55] | Yes | No | No | No | System dynamics model |
| Cao et al. [56] | Yes | No | No | No | System dynamics model |
| Roy et al. [57] | Yes | No | No | No | System dynamics model |
| This study | Yes | Yes | Yes | Yes | System dynamics model |

## 3. Methodology

The research is based on a real case and data from an environmental company in China. Taking straw as an example, the collection and treatment process of biomass energy is analyzed. The supply chain model constructed consists of farmers, acquisition stations, power plants, and pyrolysis plants. Farmers are responsible for producing and harvesting straw, which is disposed of in two ways: by direct incineration and by selling it to acquisition stations. The acquisition station is the centralized transfer center, responsible for transporting the collected straw to the power plants and pyrolysis plants. The power plants and pyrolysis plants are responsible for the final recycling of the straw, using it to generate resources such as electricity and biochar-based fertilizer, which are then sold in the market. A flow chart of the straw recycling supply chain is shown in Figure 1.

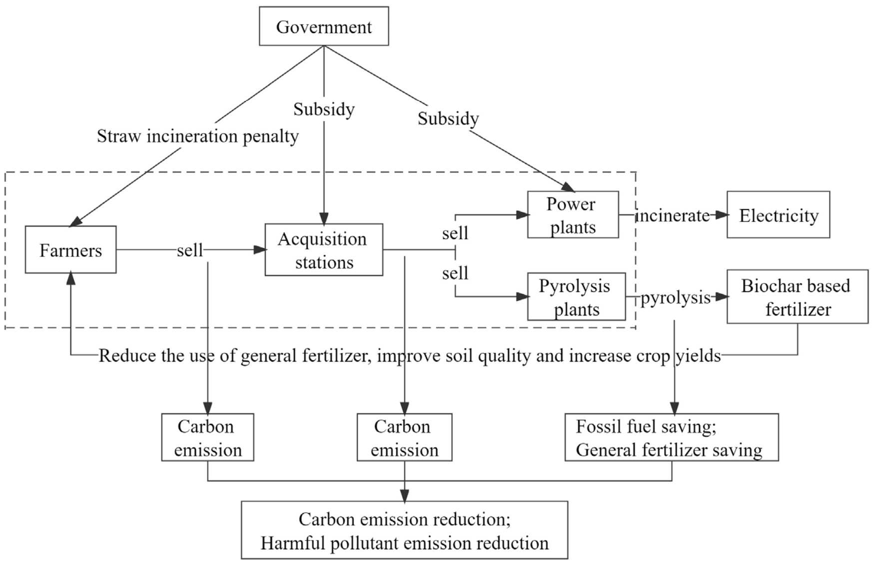



**Figure 1.** Flow chart of the straw recycling supply chain.

### *3.1. System Dynamics Model*

The system dynamics approach is mainly based on the elements' causal relationships and certain structures to analyze problems. It is not strict with data requirements and can cope with the problems of insufficient data and the difficulty of quantifying data in the modeling process. System dynamics is widely used in the study of the dynamics of supply chain logistics, capital flow, and information flow processes such as inventory management under different production modes in supply chain systems.

The basic causal relationships considered in the design of this model are as follows: government subsidies can increase the income of the farmers, acquisition stations, power plants, and pyrolysis plants, among which subsidies to the acquisition stations will indirectly affect the unit price of straw for sale, thus increasing farmers' profits, which in turn makes farmers' willingness to sell straw stronger than their willingness to directly incinerate straw, thus increasing the rate of straw sales. The increase in farmers' straw sales will further promote a reduction in resource output and emissions from power plants and pyrolysis plants. At the same time, the biochar-based fertilizer produced by the pyrolysis plants can increase the total straw yield to a certain extent, thus increasing farmers' income and straw sales rate and improving the efficiency of straw energy utilization. The causal relationship of the model is shown in Figure 2.

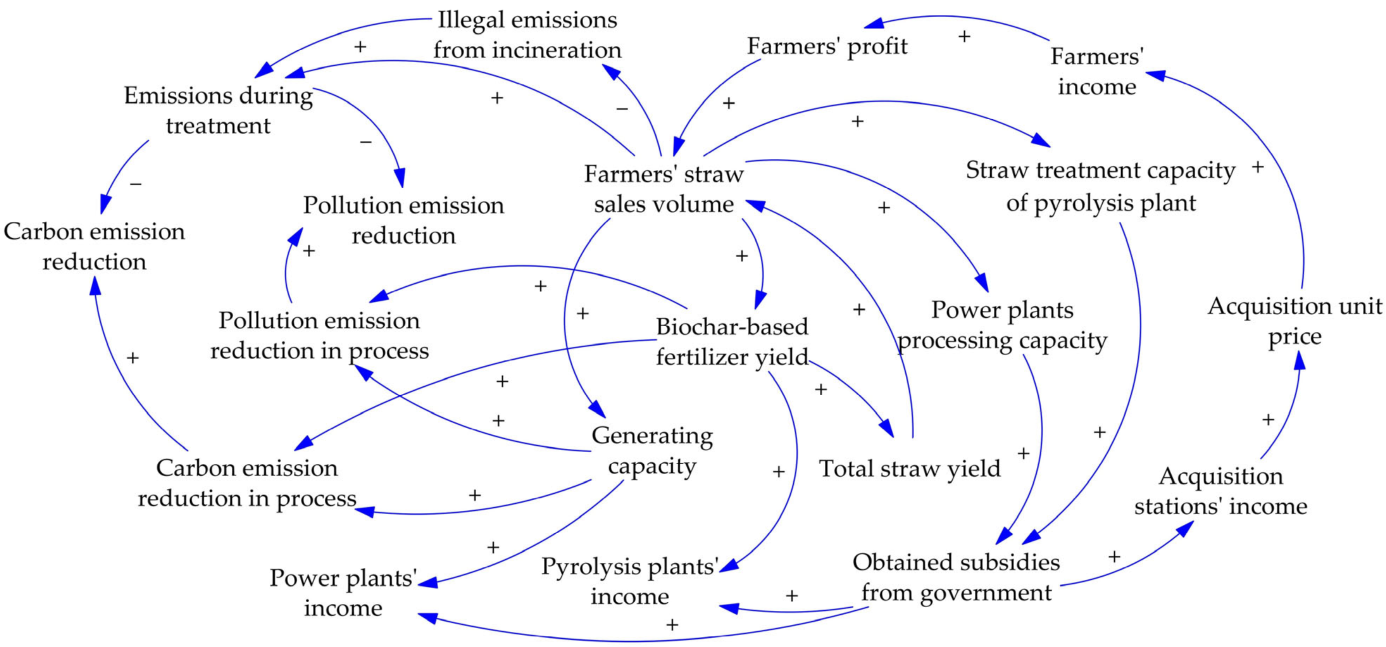



**Figure 2.** Causal loop diagram of the straw recycling supply chain.

Government subsidies promote straw energy utilization and improve the economic and environmental benefits of the straw recycling supply chain system by subsidizing acquisition stations, power plants, and pyrolysis plants, and this driving effect is shown in the model as follows:

- government subsidies → + acquisition stations' income →—acquisition unit price →—farmers' profit → + farmers' willingness to sell → + farmers' straw sales volume → + straw energy utilization.
- government subsidies → + power plants' income → + electricity yield →—fossil fuel consumption → + $CO_2$ and pollution emission →—economic and environmental benefits.
- government subsidies → + pyrolysis plants' income → + biochar-based fertilizer yield →—general fertilizer consumption →—economic and environmental benefits.

- government subsidies → + pyrolysis plants' income → + biochar-based fertilizer yield → + crop yield → + farmers' profit → + farmers' willingness to sell → + farmers' straw sales volume → + straw energy utilization.

The supply chain members involved in this model include farmers, acquisition stations, power plants, and pyrolysis plants. Indicators reflecting income include farmers' income, purchasing stations' income, power plants' income, pyrolysis plants' income, carbon emission reduction income, and pollution emission reduction income. The carbon emission reduction income refers to the economic value of this amount of coal that can be replaced in the trading market through the use of straw for power generation or pyrolysis; the pollution emission reduction income refers to the pollutant treatment cost saved by reducing the pollutant emissions through the reasonable use of straw. The system dynamics model of the straw recycling supply chain is shown in Figure 3.

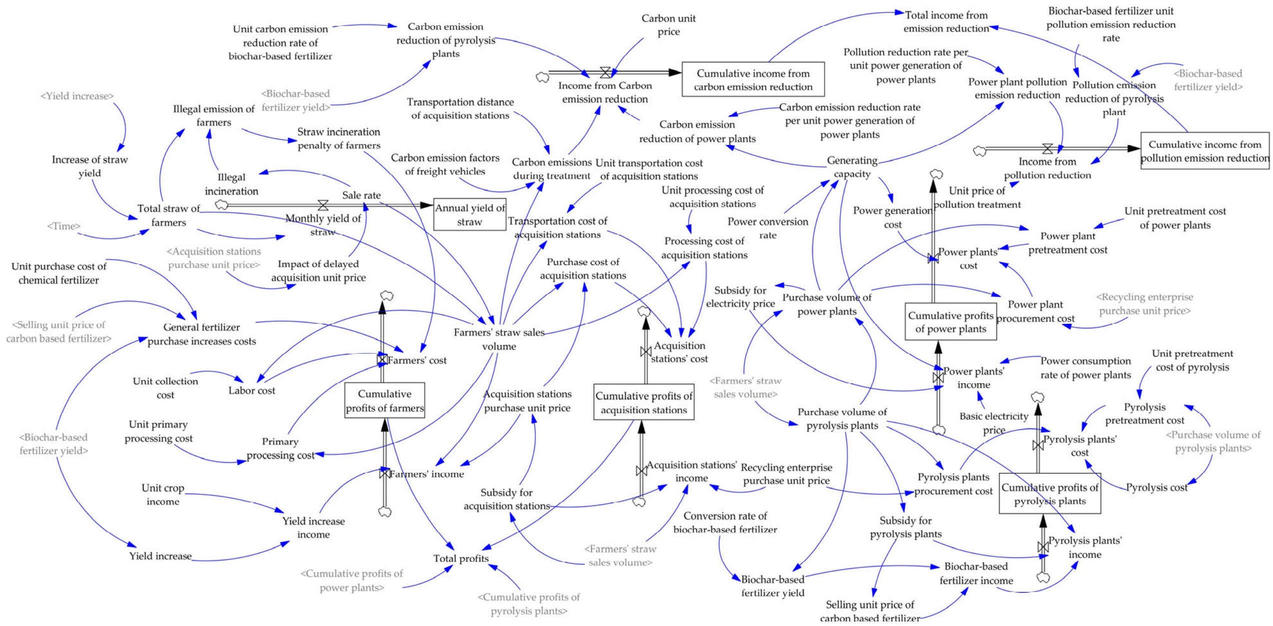


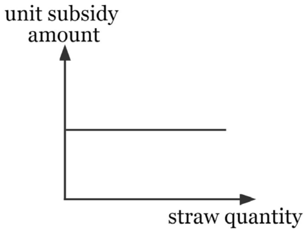
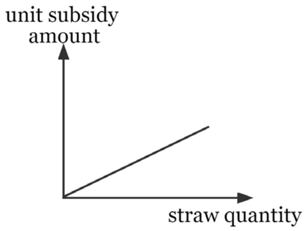
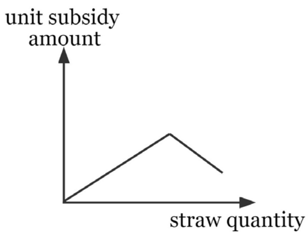

**Figure 3.** Flow diagram of the straw recycling supply chain.

### 3.2. Scenario Setting

Promoting straw energy utilization not only reduces the consumption of other energy resources but also reduces carbon and pollution emissions, so as to accelerate the construction of China's agricultural ecological civilization. However, the high input and high-risk characteristics of straw energy utilization require strong government subsidy support. As an incentive measure, different government subsidies have different effects, and domestic and foreign governments have had different subsidy policies for straw energy utilization in recent years.

Therefore, we refer to related studies [12,37] and set three different subsidy policies for the straw recycling supply chain while controlling for the same total subsidy amount. The data mainly comes from enterprise consulting and literature research. In each (data1, data2) of the equations, the data1 represents the amount of straw; its unit is tons, mainly from enterprise consulting; the data2 represents the unit subsidy amount; its unit is (CNY/t) (in particular, for the power plant subsidy, its unit is CNY/kwh), mainly from the literature [58]. And the relationship settings for data1 and data2 are also based on the literature [58]. The curves of subsidies and specific equations for the three scenarios are shown in Table 2. (ASS: acquisition station subsidy; PPS1: power plant subsidy; PPS2: pyrolysis plant subsidy.)

**Table 2.** Design of three scenarios.

<table>
<tr><th>Scenario Name</th><th>Curves of Subsidies</th><th>Equation</th></tr>
<tr><td>Unified rate policy [1]</td><td>
</td><td>ASS = with lookup (Farmers' straw sales volume ([(0, 0)–(9000, 50)], (2000, 50), (9000, 50)));<br>PPS1 = with lookup (Purchase volume of power plants ([(0, 0)–(7000, 1)], (1000, 0.25), (7000, 0.25)));<br>PPS2 = with lookup (Purchase volume of pyrolysis plants ([(0, 0)–(7000, 300)], (1000, 300), (7000, 300))).</td></tr>
<tr><td>Linear growth policy [2]</td><td>
</td><td>ASS = with lookup (Farmers' straw sales volume ([(0, 0)–(9000,100)],(2000, 10),(2778, 20),(3556, 30),(4334, 40),(5112, 50),(5890, 60),(6668, 70),(7446, 80),(8224, 90),(9000, 100)));<br>PPS1 = with lookup (Purchase volume of power plants ([(0, 0)–(7000, 1)], (1000, 0.05), (1667, 0.1), (2334, 0.15), (3001, 0.2), (3668, 0.25), (4335, 0.3), (5002, 0.35), (5669, 0.4), (6336, 0.45), (7000, 0.5)));<br>PPS2 = with lookup (Purchase volume of pyrolysis plants ([(0, 0)–(7000, 600)], (1000, 60), (1667, 120), (2334, 180), (3001, 240), (3668, 300), (4335, 360), (5002, 420), (5669, 480), (6336, 540), (7000, 600))).</td></tr>
<tr><td>Two-step policy [3]</td><td>
</td><td>ASS = with lookup (Farmers' straw sales volume ([(0, 0)–(9000, 100)], (2000, 12.4), (2778, 22.8), (3556, 36.8), (4334, 48.4), (5112, 62.4), (5890, 80), (6668, 65.5), (7446, 54.4), (8224, 44.8), (9000, 33.2)));<br>PPS1 = with lookup (Purchase volume of power plants ([(0, 0)–(7000, 1)], (1000, 0.05), (1667, 0.1), (2334, 0.15), (3001, 0.2), (3668, 0.25), (4335, 0.3), (5002, 0.35), (5669, 0.4), (6336, 0.45), (7000, 0.5)));<br>PPS2 = with lookup (Purchase volume of pyrolysis plants ([(0, 0)–(7000, 600)], (1000, 74.4), (1667, 136.8), (2334, 220.8), (3001, 290.4), (3668, 374.4), (4335, 480), (5002, 383), (5669, 326.4), (6336, 268.8), (7000, 199.2))).</td></tr>
</table>

[1] Government subsidies for acquisition stations, power plants, and pyrolysis plants are kept constant from month to month. [2] Government subsidies to acquisition stations, power plants, and pyrolysis plants increase as their straw purchases increase. [3] Government subsidies to acquisition stations, power plants, and pyrolysis plants increase as their straw purchases increase and begin to decrease after reaching a certain level.

## 4. Simulation

### *4.1. The Basic Data and Model Assumptions*

The model in this paper is based on the following basic data and assumptions. Among them, the basic data, which is the main input constant variable of the system dynamics model, mostly comes from our research on news, literature, and corporations. The basic data table is shown in Table 3.

Assumption 1: The government provides subsidies to both straw recycling enterprises, i.e., power plants and pyrolysis plants.

Assumption 2: The total straw yield is affected by the seasons. Considering the actual situation of crop harvesting in China, the straw yield is usually higher in the first and third quarters and is relatively higher in the third quarter, so we set the straw yield according to the harvesting pattern of the four seasons of the crop to reflect the influence of seasonal factors.

Assumption 3: To show the change in straw yield in four seasons, we set the total simulation time to 12 months (1 year).

Assumption 4: Both the electricity and the biochar-based fertilizer generated in this straw recycling supply chain system are fully utilized by the market, and farmers are consumers of the biochar-based fertilizer.

Assumption 5: The distance from the acquisition stations to the farmers is short and variable, set within 10 km; the distance from the acquisition stations to the power plants and the pyrolysis plants is long and relatively fixed, set at about 50 km.

**Table 3.** The basic data.

| Num | Variable Name | Values |
|---|---|---|
| 1 | Unit purchase cost of chemical fertilizer | 2500 (CNY/t) [1] |
| 2 | Unit crop income | 2000 (CNY/t) [2] |
| 3 | Unit primary processing cost | 45 (CNY/t) [3] |
| 4 | Unit collection cost | 150 (CNY/t) [1] |
| 5 | Power consumption rate of power plants | 0.1 [4] |
| 6 | Unit pretreatment cost of pyrolysis | 105 (CNY/t) [5] |
| 7 | Recycling enterprise purchase unit price | 230 (CNY/t) [5] |
| 8 | Unit processing cost of acquisition stations | 20 (CNY/t) [3] |
| 9 | Unit transportation cost of acquisition stations | 23 (CNY/t) [3] |
| 10 | Transportation distance of acquisition stations | RANDOM UNIFORM (1, 10, 0) + 50 (km) [5] |
| 11 | Basic electricity price | 0.5 (CNY/kwh) [3] |
| 12 | Unit price of pollution treatment | 2000 (CNY/t) [5] |
| 13 | Biochar-based fertilizer unit pollution emission reduction rate | 0.0636 [5] |
| 14 | Unit carbon emission reduction rate of biochar-based fertilizer | 1.28 [6] |
| 15 | Conversion rate of biochar-based fertilizer | 0.3 [5] |
| 16 | Power conversion rate | 1 [5] |
| 17 | Unit pretreatment cost of power plants | 45 (CNY/t) [5] |
| 18 | Pollution reduction rate per unit power generation of power plants | 0.0159 [7] |
| 19 | Carbon emission reduction rate per unit power generation of power plants | 0.6 [5] |
| 20 | Carbon unit price | 58 (CNY/t) [8] |
| 21 | Carbon emission factors of freight vehicles | 0.141 (kg/t × km) [4] |

[1] This data comes from the website "https://jiage.cngold.org/huafei/ (accessed on 10 January 2022)". [2] This data comes from the website "https://news.cnhnb.com/zixun/detail/420613/ (accessed on 10 January 2022)". [3] This data from Ref. [59]. [4] This data from Ref. [58]. [5] This data comes from the cooperating companies, Yunnan Water Investment Limited Corporation, Kunming, China. [6] This data comes from the website "http://gjdxkjy.neau.edu.cn/info/1021/1161.htm (accessed on 10 January 2022)". [7] This data comes from the website "http://www.tanjiaoyi.com/article-3599-1.html (accessed on 10 January 2022)". [8] This data comes from the website "http://www.tanjiaoyi.com/article-36553-1.html (accessed on 10 January 2022)".

### *4.2. Determine the Proportion*

In this model, power plants and pyrolysis plants are treated as straw recycling enterprises, and the overall benefits of the supply chain are compared and analyzed when the straw acquisition proportions of power plants and pyrolysis plants are 0.2:0.8, 0.5:0.5, and 0.8:0.2, respectively. The total benefit is composed of the variables "total income from emission reduction" and "total profits". The environmental benefits of the supply chain are represented by the variable "total income from emission reduction", which is composed of the variables "cumulative income from carbon emission reduction" and "cumulative income from pollution emission reduction". The economic benefits of the supply chain are represented by the variable "total profits", which is composed of the variables "cumulative profits of farmers", "cumulative profits of acquisition stations", "cumulative profits of power plants" and "cumulative profits of pyrolysis plants".

Each scenario is set as follows: S2-8 indicates power plant acquisition volume: pyrolysis plant acquisition volume = 0.2:0.8; S5-5 indicates power plant acquisition volume:

pyrolysis plant acquisition volume = 0.5:0.5; S8-2 indicates power plant acquisition volume: pyrolysis plant acquisition volume = 0.8:0.2.

Figure 4 shows the total benefits of the supply chain under the three straw acquisition proportions of power plants and pyrolysis plants, all of which show an increasing trend. The total benefits under scenario S2-8 are significantly higher than the other two scenarios. It can be seen that the total benefits of the supply chain increase with the increase in pyrolysis plant acquisition volume.

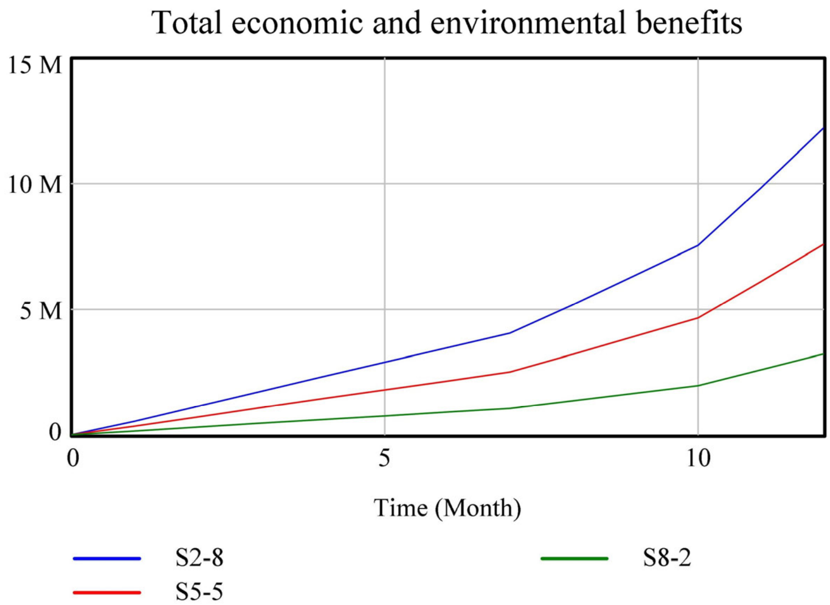



**Figure 4.** Total economic and environmental benefits under three proportions.

From the above simulation results, we can see that the role of power plants in the straw recycling supply chain is relatively weak in both economic and environmental aspects, and the proportion of straw acquisition is more favorable to the straw recycling supply chain under scenario S2-8. Therefore, we set the indicated power plant acquisition volume and pyrolysis plant acquisition volume at 0.2:0.8 and analyzed the government subsidy policy based on this proportion.

### *4.3. Optimal Subsidy Policy*

In this paper, the variables "cumulative income from carbon emission reduction", "cumulative income from pollution emission reduction", and "total income from emission reduction" are chosen to analyze the optimal subsidy policy that can effectively promote straw energy utilization and improve environmental benefits. The variables "cumulative profit of farmers", "cumulative profit of acquisition stations", "cumulative profit of power plants", "cumulative profit of pyrolysis plants", and "total profit" are chosen to analyze the optimal subsidy policy that can effectively enhance the motivation of each member of the supply chain for straw energy utilization and improve economic efficiency.

Each scenario is set as follows: S0 denotes the baseline scenario with no subsidy; S1 denotes the unified rate policy; S2 denotes the linear growth policy; and S3 denotes the two-step policy.

#### 4.3.1. Environmental Benefits of Straw Recycling Supply Chain

Figure 5a shows the trend of the cumulative income from carbon emission reduction in the straw recycling supply chain under the three different government subsidy policies. It can be seen that the cumulative income under all three subsidy policies shows an increasing trend over time and is higher than the scenario without subsidies. The cumulative income under the unified rate policy is the highest at the end of the year, 8.50% higher than those under the linear growth policy and 11.85% higher than those under the two-step policy. In other words, the unified rate subsidy can maximize the benefits of carbon emission reduction.

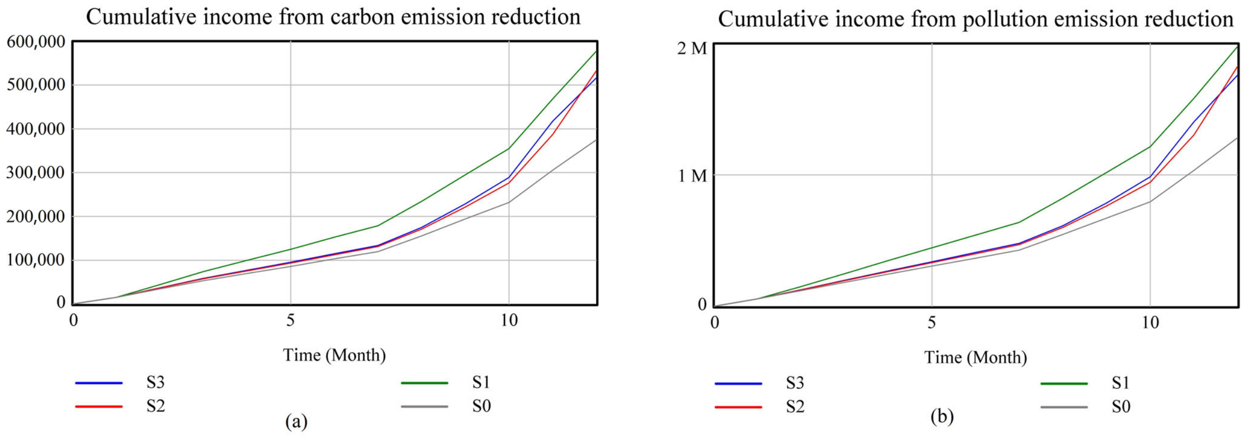



**Figure 5.** Cumulative income from carbon and pollution emission reduction under three subsidy scenarios: (**a**) Cumulative income from carbon emission reduction; (**b**) Cumulative income from pollution emission reduction.

Figure 5b shows the trend of cumulative income from pollution emission reduction in the straw recycling supply chain under three different government subsidy policies. The cumulative income under all three subsidy policies shows an increasing trend over time and is higher than the scenario without subsidies. The cumulative income under the unified rate policy is the highest at the end of the year, 8.24% higher than those under the linear growth policy and 12.34% higher than those under the two-step policy. In other words, the unified rate subsidy can maximize the benefits of pollution emission reduction.

Figure 6 shows the trend of total income from emission reduction in the straw recycling supply chain under three different government subsidy policies. It can be seen that the total income under all three subsidy policies shows an increasing trend over time and is higher than the scenario without subsidies. Since the total income from emission reduction consists of the cumulative income from carbon and pollution emission reduction, and the cumulative income from carbon and pollution emission reduction shows the same trend under the three subsidy policies, the total income from emission reduction must be consistent with the changing trend of both, i.e., the total income is highest under the unified rate policy, 8.30% higher than those under the linear growth policy, and 12.23% higher than those under the two-step policy. Accordingly, the unified rate policy can enhance the overall environmental benefits of the straw recycling supply chain system more effectively.

### 4.3.2. Economic Benefits of Straw Recycling Supply Chain

Figure 7a shows the trend of cumulative profits for farmers under three different government subsidy policies in the straw recycling supply chain. It can be seen that the cumulative profits of farmers under all three subsidy policies show an increasing trend over time and are higher than the scenario without subsidies. In the first three quarters, the cumulative profits of farmers under the unified rate policy were the highest, and the profits under the linear growth policy were the lowest. Since farmers' profits are directly related to straw yield, which is the highest in the fourth quarter, and the amount of subsidies under the linear growth policy is positively related to straw yield, when straw yield is high, subsidies are also high, so the fourth quarter becomes the fastest growing period for farmers' profits. As a result of the high-profit growth in the fourth quarter, the cumulative profit of farmers under the linear growth subsidy policy began to exceed the other two scenarios in the fourth quarter. The cumulative profit of farmers under the linear growth policy was the highest at the end of the year, 8.65% higher compared to the unified rate policy and 60.78%

higher compared to the two-step policy. Therefore, the linear growth policy has the best effect on improving farmers' income and motivation for straw energy utilization.

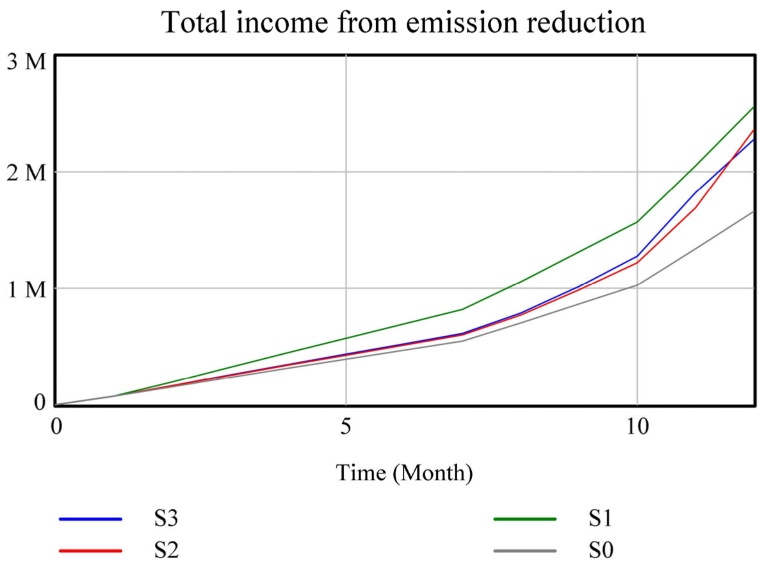



**Figure 6.** Total income from emission reduction under three subsidy scenarios.

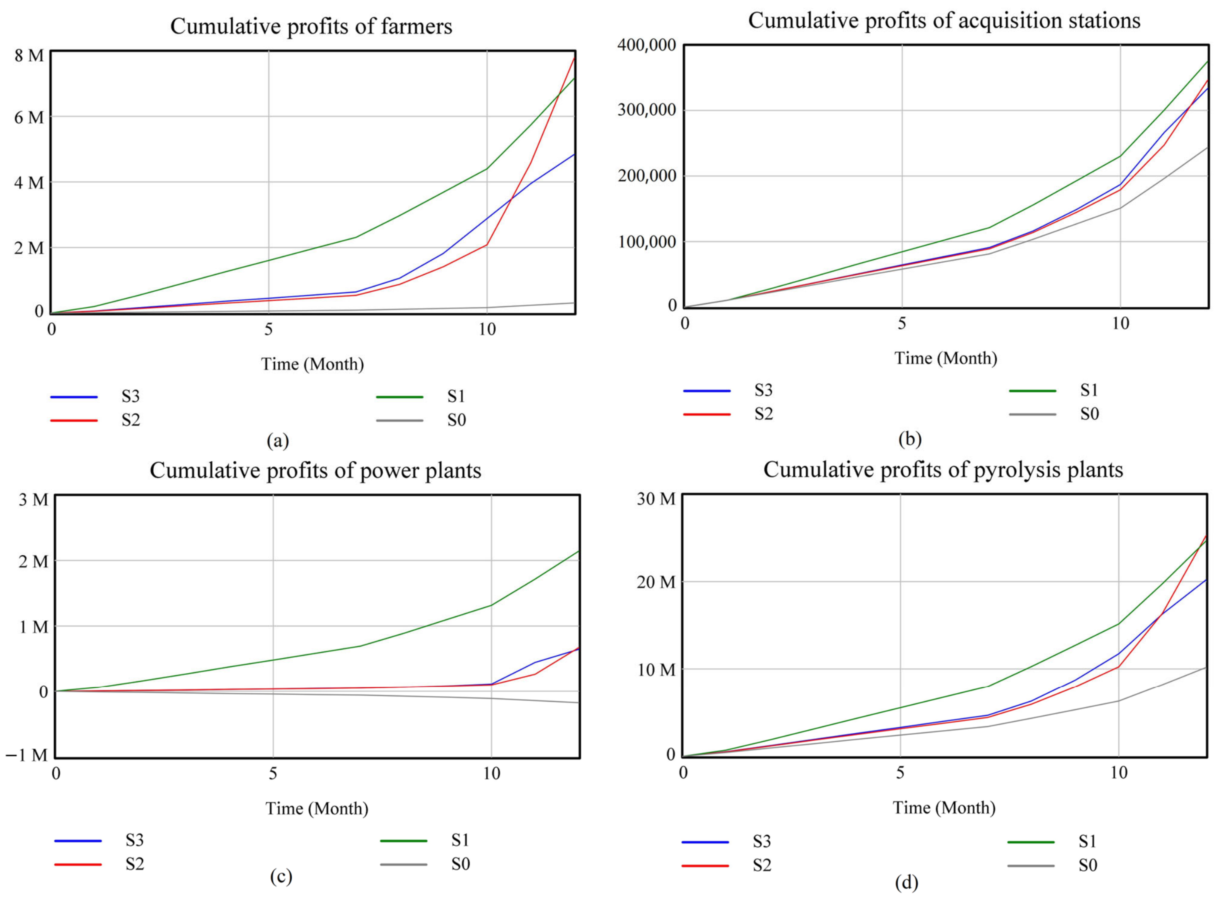



**Figure 7.** Cumulative profits of each supply chain member under three subsidy scenarios: (**a**) Cumulative profits for farmers under three subsidy scenarios; (**b**) Cumulative profits of the acquisition stations under three subsidy scenarios; (**c**) Cumulative profit of power plants under three subsidy scenarios; (**d**) Cumulative profits of pyrolysis plants under three subsidy scenarios.

Figure 7b shows the trend of cumulative profits of the acquisition stations under three different government subsidy policies in the straw recycling supply chain. The cumulative profits of the acquisition stations under all three subsidy policies show an increasing trend over time and are higher than in the scenario without subsidies. The cumulative profit of the acquisition stations under the unified rate policy is the highest at the end of the year, 8.24% higher compared to the linear growth policy and 12.34% higher compared to the two-step policy.

Figure 7c shows the trend of cumulative profit of power plants under three different government subsidy policies in the straw recycling supply chain. The cumulative profits of power plants under all three subsidy policies show an increasing trend over time and are higher than the scenario without subsidies. In terms of cumulative profits at the end of the year, the advantage of the unified rate policy is very obvious, with cumulative profits 218.73% higher compared to the linear growth policy and 230.88% higher compared to the two-step policy. Therefore, for power plants, the unified rate policy can help them obtain the highest economic benefits. There are no significant differences between the cumulative profits of power plants under the two-step subsidy policy and the linear growth policy.

Figure 7d shows the trend of cumulative profits of pyrolysis plants under three different government subsidy policies in the straw recycling supply chain. It can be seen that the cumulative profits of pyrolysis plants under all three subsidy policies show an increasing trend over time and are higher than the scenario without subsidies. The trend of the cumulative profit of pyrolysis plants is similar to that of the cumulative profit of farmers because there is a positive feedback relationship between pyrolysis plants and farmers to promote each other. The positive feedback relationship is that the biochar-based fertilizer produced by the pyrolysis plant can increase the crop yield, which can increase the straw yield and farmers' profit, and the amount of straw that can be handled by the pyrolysis plant and its profit also increases. In the first 11 months, the cumulative profit of pyrolysis plants was the highest under the unified rate policy. But in the end, the cumulative profits of pyrolysis plants under the linear growth policy began to exceed those of the other two scenarios. The cumulative profit of pyrolysis plants under the linear growth policy is the highest at the end of the year, 2.47% higher compared to the unified rate policy and 25.11% higher compared to the two-step policy. Therefore, for pyrolysis plants, the linear growth policy can help them obtain the highest economic benefits.

Figure 8 shows the trend of total profit of the supply chain under three different government subsidy policies in the straw recycling supply chain. It can be seen that the total profit under all three subsidy policies shows an increasing trend over time and is higher than the scenario without subsidies. The total profits are highest under the unified rate policy, 0.79% higher than those under the linear growth policy and 31.98% higher than those under the two-step policy. Among the four components of total profit, farmers and pyrolysis plants have the highest profit under the linear growth policy, while acquisition stations and power plants have the highest profit under the unified rate policy. Comparing the year-end cumulative profits under the optimal policies of each component, the cumulative profits of pyrolysis plants are 4.41 times higher than the cumulative profits of farmers, 67.34 times higher than the cumulative profits of acquisition stations, and 11.78 times higher than the cumulative profits of power plants. The cumulative profits of pyrolysis plants are significantly higher than the other three, so the total profits are influenced more by the profits of pyrolysis plants and show a similar trend as the profits of pyrolysis plants. Meanwhile, the advantage of the unified rate policy in the cumulative profits of power plants is prominent, while the profit performance of the other three members under the three subsidy policies has a relatively small gap. Under the combined effect of these factors, the total profit of the supply chain finally shows a higher profit under the unified rate policy and a relatively lower total profit under the other two subsidy policies. It can be seen that the unified rate policy can more effectively improve the overall economic efficiency of the straw recycling supply chain system.

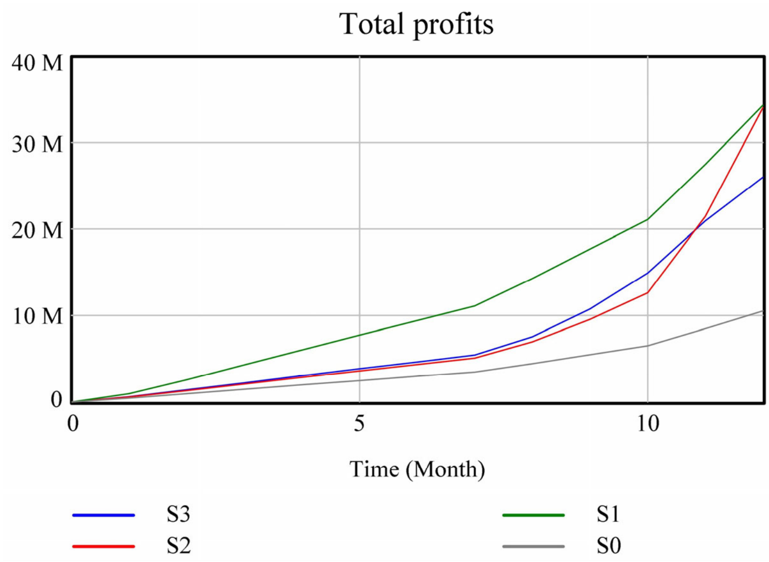



**Figure 8.** Total profits under three subsidy scenarios.

#### 4.3.3. Economic Benefits of Straw Recycling Supply Chain

The result shows that with the government subsidy, the carbon emission and pollution emissions reduction benefits are higher than that of the scenario with no subsidy. Since the composition of carbon emission benefits and pollution emission benefits is similar in this model, which is directly related to electricity generation and biochar-based fertilizer yield, both benefits have the same trend under the three subsidy policies with no significant difference. The detailed emission reduction benefits of each component and the total emission reduction benefits under each scenario are shown in Figure 9.

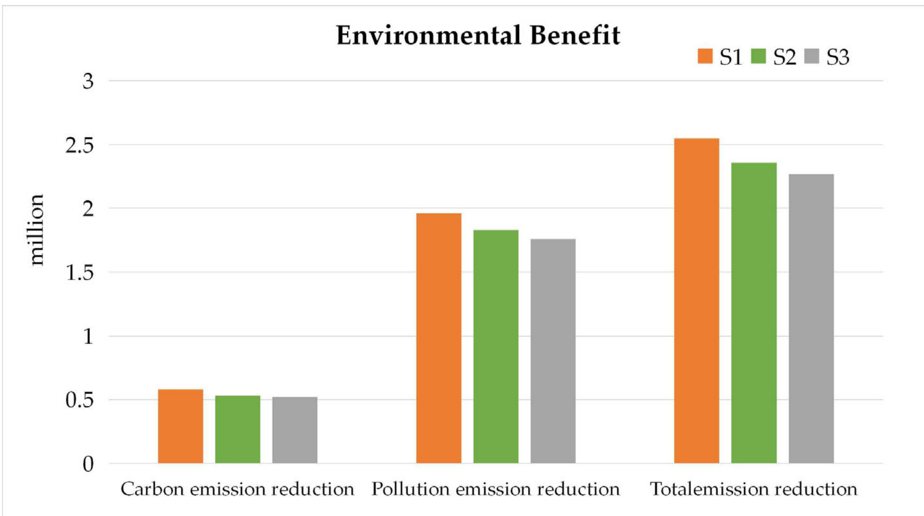



**Figure 9.** Income of carbon and pollution emission reduction and total of both.

The authors also find that, compared to the scenario with no subsidies, each member's cumulative profits are greater with any kind of subsidy policy, and the total profits are the greatest under the scenario of the unified rate policy. However, when it comes to each member's cumulative profits, the unified rate policy is not always the best option. The cumulative profits of farmers and pyrolysis plants are higher under the linear growth policy, and the cumulative profits of power plants and acquisition stations are higher under the unified rate policy. Therefore, for countries that need to vigorously develop the biomass energy pyrolysis industry, the linear growth subsidy policy can effectively support the development of pyrolysis enterprises and greatly enhance farmers' willingness to collect and sell straw. The profits of each component and the total profits under the three subsidy policies are shown in Figure 10.

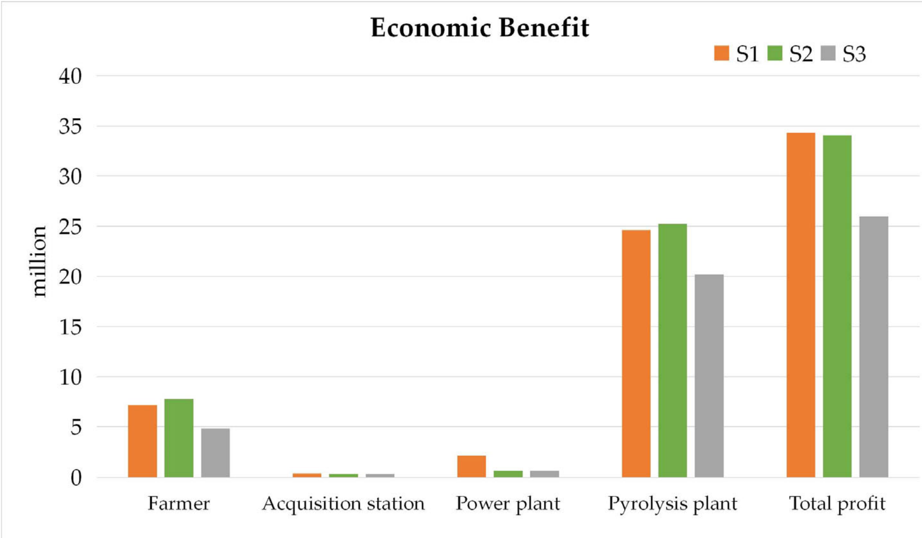



**Figure 10.** Profits of each supply chain member and total of them.

## 5. Conclusions

This paper analyzes the impact of government subsidies on biomass energy utilization through a real-world case. Taking straw as an example, a supply chain system dynamics model is constructed to analyze the economic and environmental benefits under different government subsidy policies. The results show that all three types of subsidies have a beneficial effect on the economic and environmental benefits of the straw recycling supply chain system. In other words, government subsidies can promote the development of straw energy utilization. For some countries that have not yet adopted any government subsidies for the biomass energy utilization industry, this conclusion could be a reference. These countries may have some similarities with China in some aspects, such as being agricultural production countries with abundant straw resources and a large quantity but currently unable to effectively utilize them; due to historical factors, technological limitations, or other reasons, it may not be possible to use straw in a lower-cost or intensive manner; taking the energy utilization of straw as a part of the overall development strategy requires the vigorous development of the straw recycling supply chain.

This research also analyzes the effectiveness of each subsidy policy from two perspectives, namely the environmental benefit and the economic benefit. The simulation results show that both the economic and environmental benefits of the supply chain are proven to be optimal under the unified rate policy. Therefore, it might be concluded that the unified rate policy plays a more powerful role in promoting the development of straw energy utilization. In this research, the environmental benefit is reflected by two indicators: carbon emission reduction benefits and pollution emission reduction benefits. Both indicators have a better performance under the unified rate policy. This indicates that this policy should be adopted by the government, which is struggling with environmental problems. The economic benefits are reflected in the total profits of the supply chain system. The simulation results show that the unified rate policy is better for the economic benefits of the straw recycling supply chain. However, if the government is more inclined to promote the development of straw pyrolysis and considers subsidy policies as a motivation method, the linear growth subsidy policy might be the best option.

Since the effect of seasonal factors is considered in the model, this brought unexpected gains to our study. We find that although the total profits show an increasing trend with the extension of simulation time, the yield of straw was different in the four quarters due to the seasonal characteristics. This difference in yield is shown as follows: the most straw was produced in the fourth quarter, followed by the third quarter, and the least in the first and second quarters, with no significant difference. Each income in the straw recycling supply chain system can ultimately be considered to originate from the straw at the source. Therefore, the rate of income increase, similar to the straw yield, exhibits the same pattern of seasonal variation.

Moreover, based on the preliminary investigation of the current status of straw energy utilization development and the research conclusions in this paper, we propose some policy recommendations for the government on specific assistance to members of the supply chain.

(1) For farmers, it is an effective and necessary way for the government to restrict farmers' behavior of incinerating straw through laws and regulations. Although China reached the goal of an 80% comprehensive utilization rate of straw in 2015, at the same time, 8.89% of straw was still disposed of through open incineration, resulting in resource waste and environmental pollution. The promotion of China's straw incinerating ban policy has effectively avoided these negative impacts while improving the comprehensive utilization rate of straw. The government should also strengthen the policy propaganda while implementing the straw incinerating ban policy. This can improve farmers' awareness of resource conservation and environmental protection and make them understand the benefits of straw utilization to increase crop yields, income, and environmental protection.

(2) For the acquisition stations, the most important thing is that the government needs to regulate its purchase price from a macro perspective. Earning profits is not the main purpose of the acquisition station. The key is to determine the price that can improve farmers' enthusiasm for straw energy utilization. In addition, a reasonable storage layout and straw collection methods are also issues that need attention at the acquisition station.

(3) For the recycling enterprises, also known as power plants and pyrolysis plants in this paper, they play key roles in eventually transforming agricultural waste into energy. From the front of the supply chain, these enterprises play the role of saving resources and avoiding environmental pollution caused by improper methods such as incineration. From the back end of the supply chain, the electricity and biochar-based fertilizer produced by these enterprises can reduce the consumption of fossil fuels and general fertilizers, thus playing a positive role in promoting the current goals of green development and energy structure transformation. The biggest obstacle currently faced in the positive cycle of straw energy utilization is the cost–benefit mismatch of enterprises, which can directly lead to the inability of straw recycling enterprises to form large-scale developments. Therefore, the intervention of government subsidies is very necessary. However, in the long run, the government should not only provide subsidies but also play a supervisory and guiding role in straw recycling enterprises so that they can achieve sustainable, high-quality development through innovation in business methods and upgrading of production equipment.

However, there are still some limitations in this study, and future studies can be conducted from these perspectives to make further improvements. The findings of this paper identify the most beneficial subsidy policies for the development of the biomass energization industry. However, in the long run, government subsidies also need to be considered in combination with other incentives and policy instruments in order to induce companies to achieve sustainable, high-quality development. In future research, scholars could take the perishable nature of straw and the inventory management pressure it brings into consideration and construct a more complicated yet more realistic model. Furthermore, this study is based on an idealized scenario where the promotion process of subsidy policies is very smooth. But in practice, the publicity effect or implementation progress of the subsidy policy may not be so smooth. If farmers cannot receive the information that subsidies will bring benefits, it will significantly affect the sales rate of straw, thereby affecting the efficiency of straw energy utilization. Therefore, how to strengthen the information chain about government subsidies among farmers is also an important research issue.

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