Study of the Coordination Mechanism of a Wood Processing Residue-based Reverse Supply Chain

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A revenue-sharing contract was introduced into a three-echelon wood processing residue-based reverse supply chain model to maximize the supply chain profit and realize a win-win situation for all participants. The optimal expected supply chain profits under different decision policies and the acceptable range of revenue-sharing coefficients were analyzed. Finally, the model was applied in a case study where sawdust was recycled to produce black fungus. Results showed that revenue-sharing can effectively enable supply chain coordination. Within the domain of the revenue-sharing coefficients, the production cost decreased by 5.91% and the corresponding demand increased by 16.09%, resulting in an increase of 7.73% in the supply chain profit. A comparison was made between the three-echelon and a two-echelon supply chains, and the results showed that the two-echelon supply chain would become less competitive than the three-echelon supply chain with the increase of recycling cost. Additionally, the profit shares of all parties in the three-echelon supply chain depended mainly on the revenue-sharing coefficients, which were determined by the positions of the parties and their bargaining power.

Keywords: Wood processing residues; Reverse supply chain; Revenue-sharing; Pricing mode; Coordination

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INTRODUCTION

Efficient utilization of wood residues has received increasing attention in recent years in consideration of the limited forest resources and the benefits associated with the environment and rural economy (Pokharel *et al*. 2017a). In the global market, the low-value wood residues have been used to generate bioenergy and other value-added products (Jahan-Latibari and Roohnia 2010; Cansado *et al*. 2017; Pokharel *et al*. 2017b). China, as the largest wood processing and wood products production base in the world, is also a major exporting country of wood products (Wang *et al.* 2010a; Wu *et al*. 2016; Su and Liu 2017; Zhang *et al.* 2017). However, the *status quo* of the wood processing industry in China is not as satisfactory as might be expected. The overall utilization rate of wood is only 50% to 60%, which is far lower than the rate of 80% to 90% in developed countries (Liu 2010). In addition, the treatment modes of wood processing residues are very limited. A small fraction of the residues are designated for the production of handcrafts or small articles, and some residues, such as slabs, scraps, or wood shavings, are recycled into particleboard, fiberboard, and medium-density fiberboard (MDF) board, or prepared as fertilizers (Wang *et al*. 2005; Xu *et al.* 2015). With regard to wood sawdust, some is reused for industrial purposes and a large proportion is directly combusted. Because the burning treatment is simple, this type of treatment on waste sawdust and shavings is very common in China; however, when dealt with in this manner, the wood waste cannot be sufficiently utilized. In the long run, this practice is unfavorable for the development of the wood processing industry, and, moreover, not in accordance with the requirements of green and environment protection policies (Wang *et al.* 2010b).

How to effectively utilize limited forest resources and enhance the recycling and utilization of wood residues has become a general concern for the whole society. A better solution is to establish a scientific and reasonable reverse supply chain for the utilization of wood residues. A reverse supply chain is the series of activities required to retrieve a used product from a customer and either dispose of it or reuse it. Several studies have been conducted on the construction of wood residues-based reverse supply chains. For example, Kara and Onut (2010) established a reverse logistics network for waste paper recycling and proposed a two-stage stochastic programming model to determine the optimal recycling and collection center locations and optimal flow amounts between the nodes in the network. Zhang *et al*. (2011) proposed a three-echelon reverse logistics network including a processing factory, recycling center, and collecting sites for waste wood. Burnard *et al*. (2015) presented a case study of reverse logistics of waste wood and wood products that aimed at improving the efficiency of the logistics systems through control and coordination. In consideration of the restriction of the geographical location of the waste resources on the integration of the companies that generate the waste and those that ultimately used it, Susanty *et al*. (2016) developed an internet-based Geographical Information System (or internet GIS) to help the buyer to identify the nearest producer of a specific wood waste material with the shortest route and minimum pickup cost. Xu *et al*. (2017) established the model of Online to Offline (O2O) recycled wood materials reverse logistics integration, which aimed at strengthening the “online and offline” trading to realize the unblocked recycling of wood materials. Trochu et al. (2018) proposed a mixed-integer linear program for reverse logistics network (RLN) design of wood material and conducted a scenario-based analysis to evaluate the impact of uncertainties such as supply source locations, the availability of recycled wood at the collection sites, and the various quality grades of the collected wood on the RLN design. Their study results indicated that the adjustment of the reverse logistics network can lead to the reduction of wood recycling cost. In summary, these studies either focused on the optimization of the reverse logistics network or the recycling cost of wood materials. The issues about profit distribution among the upstream and downstream members of a reverse logistics network of wood materials are rarely documented. It is known that due to the prediction difficulty, the complexity of reverse logistics, and the lack of profit-driven factors, it is very difficult to implement coordination in the supply chain, which usually leads to the failure of implementing the reverse supply chain. However, the implementation of a revenue-sharing mechanism in the reverse supply chain of wood processing residues could ensure profit coordination among the upstream and downstream members in the supply chain and coordinate the logistics flows, cash flows, and information flows among these parties to form a union of cooperation, which would be beneficial to the long-term development of the supply chain and could help remanufacturers reduce production cost, increase profits, and enhance competitiveness. In addition, this would be significant for ecological resource protection and could greatly increase the recycling and utilization of wood residues.

In this paper, a three-echelon reverse supply chain coordination model involving a wood processing mill, a third-party recycler, and a remanufacturer is established based on a revenue-sharing contract. The optimal expected profits of the reverse supply chain under different decision policies (traditional wholesale price contract model, revenue-sharing contract model), the revenue distribution among the participants in the reverse supply chain, and the revenue-sharing coefficients for realizing three win-win situations will be analyzed. Finally, the model is applied in a case study where the wood sawdust was recycled for producing black fungus. The results will provide a scientific basis and technical support for the decision-making in the reverse supply chain of wood processing residues, and all the stakeholders (remanufacturer, recycler, and wood processing mill) will benefit from the coordination of the supply chain.

METHODOLOGY

Model Description and Hypotheses

The typical supply chain contracts include wholesale price contract, quantity-flexibility contract, buy-back contract, sales-rebate contract, revenue-sharing contract, *etc*. (Cachon and Lariviere 2005). Currently, the wholesale price contract is still widely used in practice. However, the decision-makers at different echelons of the supply chain usually pursue their own maximization of profits under a wholesale price contract, and the overall profit cannot reach the maximum (Giannoccaro and Pontrandolfo 2004). The revenue-sharing contract model refers to the coordination and profit distribution mechanism on the profits generated in a supply chain according to the negotiated commercial rules among the parties in the supply chain (Pasternack 2008; Krishnan and Winter 2011; Fu *et al*. 2012; Kunter 2012). Studies on revenue-sharing contracts have been continually refined and developed and have proven to be effective in generating market shares and total profits (Dana and Spier 2001; Katok and Wu 2009; Lin *et al*. 2011; Zeng 2013; Govindan and Popiuc 2014; Zhang *et al*. 2015; Song and Gao 2018). Therefore, a revenue-sharing contract was introduced into the reverse supply chain of wood processing residue to maximize the profit of the entire supply chain and realize a win-win situation for all participants in the reverse supply chain. According to market investigations, a reverse supply chain for wood processing residues usually involves three entities, *i.e*., a wood processing mill, a third-party recycler who is responsible for collecting wood residues, and a remanufacturer who can use the residues for future production. Under a wholesale price contract, the corresponding decision process is as follows:

- According to the random market demand $D(p,\varepsilon)$ and the remanufacturing cost c_r, the remanufacturer (R) determines the optimal market price p of the remanufactured product and the optimal ordering quantity q toward the recycler;
- According to the wholesale price w_Bm provided by the wood processing mill (M) and the recycling cost c_d, the third-party recycler (D) determines the wholesale price w_Am provided to the remanufacturer;
- According to the unit cost c_m of the wood processing mill (M), the factory determines the wholesale price w_Bm.

The hypotheses for the three-echelon reverse supply chain are as follows:

(1) Suppose that the random demand function of the remanufactured product has price elasticity and can be expressed as follows:

$$D(p,\varepsilon) = y(p) + \varepsilon \quad (1)$$

$$y(p) = a - bp \quad (a > 0, b > 0) \tag{2}$$

where $D(p, \varepsilon)$ is the market demand when the price of the remanufactured product is p, and the random demand $y(p)$ is a decreasing function on the price p. Suppose that ε is a random variable, and its value range is [A,B] and A > 0, B > 0; $F(\varepsilon)$ is a probability distribution function of the random variable ε, $f(\varepsilon)$ is the probability density function of the random variable ε, and μ is the mean value of the random variable ε.

(2) All parties in the reverse supply chain are risk-neutral and fully rational, *i.e.*, they make decisions based on the principle of maximizing expected profits. The information in the reverse supply chain is completely symmetrical, and both the stockout loss cost and the commodity salvage are zero.

(3) Under the revenue-sharing contract, it is supposed that the revenue-sharing coefficient between the remanufacturer and the wood processing residues recycler is ϕ_A ($0 < \phi_A < 1$), and that the revenue-sharing coefficient between the wood processing residue recycler and the wood processing mill is ϕ_B ($0 < \phi_B < 1$). The remanufacturer can obtain part of the sales revenue of the product (ϕ_A), the wood processing residue recycler can actually attain the sales revenue of $\phi_B (1 - \phi_A)$, while the remaining $(1- \phi_B)(1 - \phi_A)$ can be obtained by the wood processing mill. Under the mode of the revenue-sharing contract, the wholesale price provided by the wood processing residue recycler to the remanufacturer is w_{Ac}, and the wholesale price provided by the wood-processing mill to the wood processing residue recycler is w_{Bc}.

The reverse supply chain of the wood processing residues under the mode of the revenue-sharing contract is shown in Fig. 1.

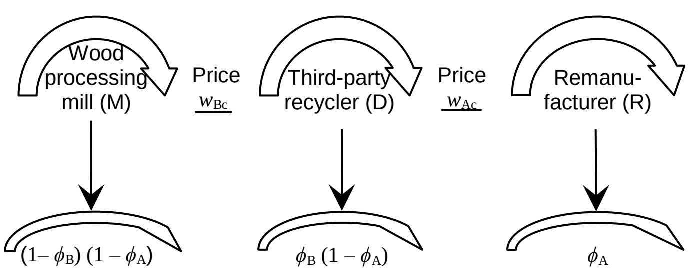

Fig. 1. Structure of reverse supply chain under revenue-sharing contract

Modeling Approach

Optimal decision on the reverse supply chain under the wholesale-price contract

Under the mode of the wholesale price contract, the profit function of the remanufacturer who utilizes the wood processing residues to produce products can be expressed as follows:

$$\Pi_{Rm}(q,p) = \begin{cases} pD(p,\varepsilon) - (w_{Am} + c_r)q, & D(p,\varepsilon) \le q \\ pq - (w_{Am} + c_r)q, & D(p,\varepsilon) > q \end{cases} \tag{3}$$

Equation 3 indicates that when the market demand of product $D(p,\varepsilon)$ is less than the quantity of order q, the sales quantity of the product is equal to the market demand; when the market demand of the product is greater than the order quantity, the sales quantity of the remanufacturer is limited to the order quantity q, and the expected profit of the remanufacturer is determined by the difference between the sales revenue and the order and production costs.

Let $z = q - y(p)$, where z denotes the inventory factor, then the expected profit function of the remanufacturer can be revised as follows:

$$\varPi_{\mathrm{Rm}}(z,p) = p\left[y(p)+\min(z,\varepsilon)\right]-(w_{\mathrm{Am}}+c_{\mathrm{r}})\left[y(p)+z\right] \tag{4}$$

Similarly, under the traditional wholesale-price contract, the profit function of the wood processing residue recycler and the wood processing mill can be respectively calculated by Eqs. 5 and 6. The profit obtained by the recycler is the wholesale revenue from the remanufacturer subtracted by the cost paid to the wood processing mill and its production cost; the profit obtained by the wood processing mill is determined by the difference between the wholesale revenue from the recycler and its production cost.

$$\varPi_{\mathrm{Dm}}(z,p) = w_{\mathrm{Am}}\left[y(p)+z\right]-\left(w_{\mathrm{Bm}}+c_{\mathrm{d}}\right)\left[y(p)+z\right] \tag{5}$$

$$\varPi_{\mathrm{Mm}}(z,p) = w_{\mathrm{Bm}}\left[y(p)+z\right]-c_{\mathrm{m}}\left[y(p)+z\right] \tag{6}$$

Based on Eqs. 4 through 6, the remanufacturer can determine with complete information the optimal order quantity and the optimal market price, which are also the optimal order quantity and market price of the whole supply chain under the traditional wholesale-price contract. Concerning Eq. 4, the expected profit function of the remanufacturer can be obtained as follows:

$$\begin{aligned} E\left[\varPi_{\mathrm{Rm}}(z,p)\right] &= py(p)+p\int_0^z \varepsilon f(\varepsilon)d\varepsilon + pz\left[1-F(z)\right]-(w_{\mathrm{Am}}+c_{\mathrm{r}})\left[y(p)+z\right] \\ &= p\left[y(p)+z\right]-p\int_0^z F(\varepsilon)d\varepsilon-(w_{\mathrm{Am}}+c_{\mathrm{r}})\left[y(p)+z\right] \end{aligned} \tag{7}$$

Solving the first-order and the second-order partial derivative for the variables z and p in Eq. 7, the following results can be obtained:

$$\frac{\partial E\left[\varPi_{\mathrm{Rm}}(z,p)\right]}{\partial z} = p - pF(z) - w_{\mathrm{Am}} - c_{\mathrm{r}} \tag{8}$$

$$\frac{\partial^2 E\left[\varPi_{\mathrm{Rm}}(z,p)\right]}{\partial z^2} = -pf(z) \tag{9}$$

$$\frac{\partial E\left[\varPi_{\mathrm{Rm}}(z,p)\right]}{\partial p} = y(p)+z+y'(p)\left[p-w_{\mathrm{Am}}-c_{\mathrm{r}}\right]-\int_0^z F(\varepsilon)d\varepsilon = a-2bp+z+bw_{\mathrm{Am}}+bc_{\mathrm{r}}-\int_0^z F(\varepsilon)d\varepsilon \tag{10}$$

$$\frac{\partial^2 E\left[\varPi_{\mathrm{Rm}}(z,p)\right]}{\partial p^2} = -2b \tag{11}$$

It is known from Eqs. 9 and 11 that the profit function of the remanufacturer is a convex function of z and p, respectively. Let Eqs. 8 and 10 be equal to 0, respectively, and combine the two equations to calculate the optimal inventory factor, z°, and the optimal market price, p°, of the remanufacturer under the traditional wholesale-price contract. The two factors are also the optimal decision variables under the traditional wholesale price contract of the entire supply chain:

$$F(z^{\mathrm{o}}) = \frac{p^{\mathrm{o}} - w_{\mathrm{Am}} - c_{\mathrm{r}}}{p^{\mathrm{o}}} \tag{12}$$

$$p^{\mathrm{o}} = \frac{a + z^{\mathrm{o}} + bw_{\mathrm{Am}} + bc_{\mathrm{r}} - \int_0^z F(\varepsilon)d\varepsilon}{2b} \tag{13}$$

According to $z = q - y(p)$, z°, and $y(p)$, the optimal order quantity q° can be solved; additionally, the expected profit of the wood processing mill and the expected profit of the third-party recycler can be respectively solved. The integral maximum expected profit of the supply chain under the traditional wholesale-price contract can be computed as follows:

$$E\left[\Pi^{\mathrm{o}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right] = E\left[\Pi^{\mathrm{o}}_{\mathrm{Rm}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right] + E\left[\Pi^{\mathrm{o}}_{\mathrm{Dm}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right] + E\left[\Pi^{\mathrm{o}}_{\mathrm{Mm}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right] \tag{14}$$

Optimal decisions in the reverse supply chain coordinated by revenue-sharing contract under decentralized decision-making

According to the model description and hypotheses, under the revenue-sharing contract, the profit functions of the remanufacturer ($\Pi_{\mathrm{Rc}}(z,p)$), the wood processing residue recycler ($\Pi_{\mathrm{Dc}}(z,p)$), and the wood-processing mill ($\Pi_{\mathrm{Mc}}(z,p)$) can be respectively expressed as follows:

$$\Pi_{\mathrm{Rc}}(z,p) = \phi_{\mathrm{A}} p\left[y(p) + \min(z,\varepsilon)\right] - (w_{\mathrm{Ac}} + c_{\mathrm{r}})\left[y(p) + z\right] \tag{15}$$

$$\Pi_{\mathrm{Dc}}(z,p) = \phi_{\mathrm{B}}\left\{(1-\phi_{\mathrm{A}})\, p[y(p) + \min(z,\varepsilon)] + w_{\mathrm{Ac}}\left[y(p) + z\right]\right\} - (w_{\mathrm{Bc}} + c_{\mathrm{d}})[y(p) + z] \tag{16}$$

$$\Pi_{\mathrm{Mc}}(z,p) = (1-\phi_{\mathrm{B}})\left\{(1-\phi_{\mathrm{A}}) p\left[y(p) + \min(z,\varepsilon)\right] + w_{\mathrm{Ac}}\left[y(p) + z\right]\right\} + w_{\mathrm{Bc}}\left[y(p) + z\right] - c_{\mathrm{m}}\left[y(p) + z\right] \tag{17}$$

According to the model hypotheses, each party in the supply chain coordinated by the revenue-sharing contract under decentralized decision-making is fully rational and will determine the parameter (z, p) on the basis of their respective profit functions, so as to maximize their own profits.

The expected profit function of the remanufacturer can be expressed as follows:

$$\begin{aligned} \mathrm{E}\left[\Pi_{\mathrm{Rc}}(z,p)\right] &= \phi_{\mathrm{A}} p\left\{y(p) + \int_0^z \varepsilon f(\varepsilon)d\varepsilon + z\left[1 - F(z)\right]\right\} - (w_{\mathrm{Ac}} + c_{\mathrm{r}})\left[y(p) + z\right] \\ &= \phi_{\mathrm{A}} p\left[y(p) + z\right] - \phi_{\mathrm{A}} p\int_0^z F(\varepsilon)d\varepsilon - (w_{\mathrm{Ac}} + c_{\mathrm{r}})\left[y(p) + z\right] \end{aligned} \tag{18}$$

The remanufacturer's optimal inventory factor z^*_{R} and optimal market price p^*_{R} under the revenue-sharing contract can be obtained as follows:

$$F\left(z^*_{\mathrm{R}}\right) = \frac{p^*_{\mathrm{R}}\phi_{\mathrm{A}} - w_{\mathrm{Ac}} - c_{\mathrm{r}}}{p^*_{\mathrm{R}}\phi_{\mathrm{A}}} \tag{19}$$

$$p^*_{\mathrm{R}} = \frac{\phi_{\mathrm{A}}\left(a + z^*_{\mathrm{R}}\right) + bw_{\mathrm{Ac}} + bc_{\mathrm{r}} - \phi_{\mathrm{A}}\int_0^{z^*_{\mathrm{R}}} F\left(\varepsilon\right)d\varepsilon}{2\phi_{\mathrm{A}} b} \tag{20}$$

The expected profit function of the third-party recycler is shown as follows:

$$\mathrm{E}\left[\Pi_{\mathrm{Dc}}(z,p)\right]=\phi_{\mathrm{B}}\left\{(1-\phi_{\mathrm{A}})p\left[y(p)+\int_0^z\varepsilon f(\varepsilon)d\varepsilon+z(1-F(z))\right]+w_{\mathrm{Ac}}\left[y(p)+z\right]\right\}-(w_{\mathrm{Bc}}+c_{\mathrm{d}})\left[y(p)+z\right]$$
$$=\left[\phi_{\mathrm{B}}(1-\phi_{\mathrm{A}})p+\phi_{\mathrm{B}}w_{\mathrm{Ac}}-w_{\mathrm{Bc}}-c_{\mathrm{d}}\right]\left[y(p)+z\right]-\phi_{\mathrm{B}}(1-\phi_{\mathrm{A}})p\int_0^z F(\varepsilon)d\varepsilon \tag{21}$$

The optimal inventory factor z_{D}^* and optimal market price p_{D}^* of the third-party recycler under the revenue-sharing contract and decentralized decision-making can be obtained as follows:

$$F\left(z_{\mathrm{D}}^*\right)=\frac{p_{\mathrm{D}}^*\left(1-\phi_{\mathrm{A}}\right)\phi_{\mathrm{B}}+w_{\mathrm{Ac}}\phi_{\mathrm{B}}-w_{\mathrm{Bc}}-c_{\mathrm{d}}}{p_{\mathrm{D}}^*\left(1-\phi_{\mathrm{A}}\right)\phi_{\mathrm{B}}} \tag{22}$$

$$p_{\mathrm{D}}^*=\frac{-\phi_{\mathrm{B}}w_{\mathrm{Ac}}b+w_{\mathrm{Bc}}b+c_{\mathrm{d}}b+\phi_{\mathrm{B}}\left(1-\phi_{\mathrm{A}}\right)\left(a+z_{\mathrm{D}}^*\right)-\phi_{\mathrm{B}}\left(1-\phi_{\mathrm{A}}\right)\int_0^{z_{\mathrm{D}}^*}F\left(\varepsilon\right)d\varepsilon}{2b\phi_{\mathrm{B}}\left(1-\phi_{\mathrm{A}}\right)} \tag{23}$$

The expected profit function of the wood processing mill is shown as follows:

$$\mathrm{E}\left[\Pi_{\mathrm{Mc}}(z,p)\right]=(1-\phi_{\mathrm{B}})\left\{(1-\phi_{\mathrm{A}})p\left[y(p)+\int_0^z\varepsilon f(\varepsilon)d\varepsilon+z(1-F(z))\right]+w_{\mathrm{Ac}}[y(p)+z]\right\}+w_{\mathrm{Bc}}\left[y(p)+z\right]-c_{\mathrm{m}}\left[y(p)+z\right]$$
$$=\left[(1-\phi_{\mathrm{B}})(1-\phi_{\mathrm{A}})p+(1-\phi_{\mathrm{B}})w_{\mathrm{Ac}}+w_{\mathrm{Bc}}-c_{\mathrm{m}}\right]\left[y(p)+z\right]-(1-\phi_{\mathrm{B}})(1-\phi_{\mathrm{A}})p\int_0^z F(\varepsilon)d\varepsilon \tag{24}$$

The optimal inventory factor z_{M}^* and optimal market price p_{M}^* for the wood-processing mill under the revenue-sharing contract and decentralized decision-making can be obtained as follows:

$$F\left(z_{\mathrm{M}}^*\right)=\frac{p_{\mathrm{M}}^*\left(1-\phi_{\mathrm{A}}\right)\left(1-\phi_{\mathrm{B}}\right)+w_{\mathrm{Ac}}\left(1-\phi_{\mathrm{B}}\right)+w_{\mathrm{Bc}}-c_{\mathrm{m}}}{p_{\mathrm{M}}^*\left(1-\phi_{\mathrm{A}}\right)\left(1-\phi_{\mathrm{B}}\right)} \tag{25}$$

$$p_{\mathrm{M}}^*=\frac{(1-\phi_{\mathrm{A}})(1-\phi_{\mathrm{B}})(a+z_{\mathrm{M}}^*)-b\left[(1-\phi_{\mathrm{B}})w_{\mathrm{Ac}}+(w_{\mathrm{Bc}}-c_{\mathrm{m}})\right]-(1-\phi_{\mathrm{A}})(1-\phi_{\mathrm{B}})\int_0^{z_{\mathrm{M}}^*}F(\varepsilon)d\varepsilon}{2b(1-\phi_{\mathrm{A}})(1-\phi_{\mathrm{B}})} \tag{26}$$

Realization of the expected profit of each party in the reverse supply chain with revenue-sharing contract under centralized decision-making

Under centralized decision-making with the revenue-sharing contract it was not necessary to consider the profit shift among the wood processing mill, the third-party recycler, and the remanufacturer in the reverse supply chain. The integral expected profit was only determined by the sales revenue of the final products and the total cost of the entire supply chain. The expected profit function of the integral supply chain is shown as follows:

$$E\left[\Pi(z,p)\right]=py(p)+p\int_0^z\varepsilon f(\varepsilon)d\varepsilon+pz\left[1-F(z)\right]-(c_{\mathrm{r}}+c_{\mathrm{d}}+c_{\mathrm{m}})\left[y(p)+z\right]$$
$$=p\left[y(p)+z\right]-p\int_0^z F(\varepsilon)d\varepsilon-(c_{\mathrm{r}}+c_{\mathrm{d}}+c_{\mathrm{m}})\left[y(p)+z\right] \tag{27}$$

The integral optimal inventory factor z^* and the integral optimal market price p^* can be obtained as follows:

$$F\left(z^*\right)=\frac{p^*-(c_{\mathrm{r}}+c_{\mathrm{d}}+c_{\mathrm{m}})}{p^*} \tag{28}$$

$$p^*=\frac{a+z^*+b(c_{\mathrm{r}}+c_{\mathrm{d}}+c_{\mathrm{m}})-\int_0^{z^*}F(\varepsilon)d\varepsilon}{2b} \tag{29}$$

Coordination mechanism

There are two objectives in a revenue-sharing contract (Giannoccaro and Pontrandolfo 2004). The first one is that the optimal solution to the supply chain with the revenue-sharing contract is the Nash equilibrium point, which means that all the entities and the entire supply chain can optimize the profit and obtain more profits without sacrificing the benefits of the other entity. The second is that all the entities in the supply chain are expected to attain more profits under the revenue-sharing contract than under traditional wholesale-price contract. To realize the first objective, the following constraints must be satisfied:

$$F\left(z^*\right)=F\left(z_{\mathrm{R}}^*\right)=F\left(z_{\mathrm{D}}^*\right)=F\left(z_{\mathrm{M}}^*\right) \tag{30}$$

$$p^*=p_{\mathrm{R}}^*=p_{\mathrm{D}}^*=p_{\mathrm{M}}^* \tag{31}$$

Therefore,

$$w_{\mathrm{Ac}}=\phi_{\mathrm{A}}\left(c_{\mathrm{r}}+c_{\mathrm{d}}+c_{\mathrm{m}}\right)-c_{\mathrm{r}}>0\Rightarrow\phi_{\mathrm{A}}>\frac{c_{\mathrm{r}}}{c_{\mathrm{r}}+c_{\mathrm{d}}+c_{\mathrm{m}}} \tag{32}$$

$$w_{\mathrm{Bc}}=\phi_{\mathrm{B}}\left(c_{\mathrm{d}}+c_{\mathrm{m}}\right)-c_{\mathrm{d}}>0\Rightarrow\phi_{\mathrm{B}}>\frac{c_{\mathrm{d}}}{c_{\mathrm{d}}+c_{\mathrm{m}}} \tag{33}$$

To realize the second objective, the following constraints must be satisfied:

$$E\left[\Pi_{\mathrm{Rc}}\left(z^*,p^*\right)\right]>E\left[\Pi_{\mathrm{Rm}}\left(z^{\mathrm{o}},p^{\mathrm{o}}\right)\right]\Rightarrow\phi_{\mathrm{A}}>\frac{E\left[\Pi_{\mathrm{Rm}}\left(z^{\mathrm{o}},p^{\mathrm{o}}\right)\right]}{E\left[\Pi^*\left(z^*,p^*\right)\right]} \tag{34}$$

$$E\left[\Pi_{\mathrm{Mc}}\left(z^*,p^*\right)\right]>E\left[\Pi_{\mathrm{Mm}}\left(z^{\mathrm{o}},p^{\mathrm{o}}\right)\right]\Rightarrow(1-\phi_{\mathrm{B}})(1-\phi_{\mathrm{A}})>\frac{E\left[\Pi_{\mathrm{Mm}}\left(z^{\mathrm{o}},p^{\mathrm{o}}\right)\right]}{E\left[\Pi^*\left(z^*,p^*\right)\right]} \tag{35}$$

$$E\left[\Pi_{\mathrm{Dc}}\left(z^*,p^*\right)\right]>E\left[\Pi_{\mathrm{Dm}}\left(z^{\mathrm{o}},p^{\mathrm{o}}\right)\right]\Rightarrow\phi_{\mathrm{B}}(1-\phi_{\mathrm{A}})>\frac{E\left[\Pi_{\mathrm{Dm}}\left(z^{\mathrm{o}},p^{\mathrm{o}}\right)\right]}{E\left[\Pi^*\left(z^*,p^*\right)\right]} \tag{36}$$

Data Sources

The model was applied in a reverse supply chain based on wood processing residues. Three parties are included in this supply chain: a remanufacturer who uses wood processing residues to produce edible fungus, a third-party recycler who is responsible for collecting saw mill residues, producing sawdust and wood chips, and selling the processed residues to the remanufacturer, and a wood processing mill. The field investigation showed that the remanufacturer incurred a lot of expenses from wood residue procurement and inventory to ensure the operation of the supply chain, which led to the higher production cost of the fungus. In the reverse supply chain, the three parties still adopted the profit distribution mode under traditional market conditions, and the efficiency of the entire supply chain was not satisfied. To improve the expected profits of all the parties, the optimal expected profits of the reverse supply chain under different decision policies (wholesale price contract model, revenue-sharing contract model), different revenue distributions among the participants in the reverse supply chain, and the different contract parameters for realizing three win-win situations were analyzed.

Suppose the function of the random market demand against the elastic price p basically meets $D(p,\varepsilon) = 550 - 0.015p + \varepsilon$ (unit: 10,000 bags); then, the probability density function of the random variable ε is $f(\varepsilon) = 1/10$, and the probability distribution function is $F(\varepsilon) = \varepsilon/10$. The coefficient of contract between the fungus production enterprise and the third-party recycler is ϕ_A, and the coefficient of contract between the third-party recycler and the wood-processing mill is ϕ_B. The parameters in the reverse supply chain are presented in Table 1.

Table 1. Model Parameters for the Reverse Supply Chain

Parameter	Explanation	Value
c_r	Unit production cost of the fungus production enterprise (US$/10,000 bags)	1,397
c_d	Unit production cost of the third-party recycler (US$/10,000 bags)	324
c_m	Unit production cost of the wood processing mill (US$/10,000 bags)	235
w_{Am}	Selling price of processed residues to the fungus production enterprise without revenue-sharing contract (US$/10,000 bags)	1,029
w_{Bm}	Selling price of mill residues to the third-party recycler without revenue-sharing contract (US$/10,000 bags)	441
a	Constant of market demand	550
b	Elasticity coefficient of market demand	0.015
ε	Random market demand variable	$\varepsilon \in (0,10)$

RESULTS AND DISCUSSION

Optimal Decision-making under Different Contracts

The optimal decisions under different modes, such as the optimal inventory factor and the optimal selling price of fungus under different contracts, are summarized in Table 2. According to the Nash equilibrium, the conditions of revenue sharing, the optimal selling price p^*, and the optimal inventory factor z^* under centralized decision-making are the same as those under decentralized decision-making. Under the market condition of price elasticity of demand, the wholesale price of edible fungus for the remanufacturer, after implementation of the revenue-sharing contract, deceased by 5.91%, from 3,924 US$/10,000 bags to 3,692 US$/10,000 bags, compared to that without the revenue-sharing contract. However, the price reduction also promoted the increase in market demand for the product. The demand for fungus increased from 153.5 thousand bags to 178.2 thousand bags, an increase of 16.09%.

Table 2. Optimized Decision Variables under Different Contracts

Optimized Decision-making Under Different Modes	Traditional Wholesale Price Mode			Revenue-sharing Contract Mode Under Centralized Decision-making		
	Optimal inventory factor z° (10,000 bags)	Optimal market price of product p° (US$/10,000 bags)	Market demand $D(p^{\circ}, z^{\circ})$ (10,000 bags)	Optimal inventory factor z^{*} (10,000 bags)	Optimal market price of product p^{*} (US$/10,000 bags)	Market demand $D(p^{*}, z^{*})$ (10,000 bags)
Value	3.82	3,924	153.5	4.70	3,692	178.2

Compared with the same supply chain with two participants (a wood processing mill and a single remanufacturer), the recycling cost of wood sawdust would be significantly higher than that in the three-echelon supply chain because the recycler is also responsible for collecting and delivering the sawdust to the production facility. When the increase of the recycling cost ranged from 0 to 100%, the wholesale price of fungus would increase from 3,793 US$/10,000 bags to 3,954 US$/10,000 bags, and the demand for fungus would decrease from 167.37 thousand bags to 150.45 thousand bags under the wholesale price mode. Similarly, the wholesale price of fungus would increase from 3,692 US$/10,000 bags to 3,852 US$/10,000 bags, and the demand for fungus would decrease from 178.2 thousand bags to 161.20 thousand bags when the recycling cost was increased by 0 to 100% under the revenue-sharing contract mode.

Optimal Expected Profit of the Supply Chain under Different Contracts

The optimal expected profits of each party in the three-echelon supply chain under different contract modes are summarized in Table 3. Under the traditional wholesale price mode, the expected profits of the remanufacturer, the third-party recycler, and the wood-processing mill were US$ 227,118, US$ 40,640, and US$ 31,609, respectively. The expected profit of the entire supply chain was the sum of the three parties, which was US$ 299,366. Under the revenue-sharing contract, the parties in the supply chain can effectively cooperate with each other and make the optimal decisions based on the target of maximizing the profit of the entire supply chain. The expected profit would be US$ 322,500, greater than that under the traditional wholesale price mode, which indicated that the supply chain could be optimized by cooperation and profit-sharing among the parties within the supply chain. However, it also indicated that the improvement of the total profit was only approximately 7% due to the constraint of elasticity demand of the market.

Table 3. Optimized Expected Profits of the Supply Chain under Different Contract Modes

Expected Profits of Different Parties Under Different Modes	Traditional Wholesale Price Mode				Revenue-sharing Contract Mode Under Centralized Decision
	Expected profit of the remanufacturer $E\left[\Pi_{\mathrm{Rm}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right]$	Expected profit of the recycler $E\left[\Pi_{\mathrm{Dm}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right]$	Expected profit of the wood processing mill $E\left[\Pi_{\mathrm{Mm}}\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right]$	Expected profit of the entire supply chain $E\Pi^{\mathrm{o}}\left[\left(z^{\mathrm{o}}, p^{\mathrm{o}}\right)\right]$	Expected profit of the entire supply chain $E\Pi^{*}\left[\left(z^{*}, p^{*}\right)\right]$
Expected Profit (US$)	227,118	40,640	31,609	299,366	322,500

With regard to the same supply chain with two participants, the expected profit of the entire supply chain would change from US$ 304,044 to US$ 249,147 under the wholesale price mode when the increase of the recycling cost ranged from 0 to 100%. Similarly, the expected profit of the entire supply chain would change from US$ 322,500 to US$ 264,496 under the revenue-sharing contract mode. Therefore, when the recycling cost was the same for the two-echelon and three-echelon supply chains, the expected profit would be the same because the optimal selling price and inventory factor under centralized decision-making were the same for both revenue-sharing supply chains regardless of the transaction on wood residues.

The Acceptable Range of the Revenue-sharing Coefficients

To achieve a win-win situation for all the parties within the three-echelon reverse supply chain with revenue-sharing contract, the revenue-sharing coefficients ϕ_{A} and ϕ_{B} must satisfy the following constraint conditions simultaneously, including $\phi_{\mathrm{A}} > 0.72$, $\phi_{\mathrm{A}} > 0.70$, $\phi_{\mathrm{B}} > 0.58$, $\phi_{\mathrm{B}}(1 - \phi_{\mathrm{A}}) > 0.13$, and $(1 - \phi_{\mathrm{B}})(1 - \phi_{\mathrm{A}}) > 0.10$. The constraints are shown in Fig. 2. The shaded area is just the acceptable range for parameters ϕ_{A} and ϕ_{B} when the win-win was realized. The revenue-sharing coefficient between the remanufacturer and the third-party recycler was between 0.72 and 0.77, and the revenue-sharing coefficient between the recycler and the wood-processing mill was between 0.58 and 0.66. The coordinates of three intersections formed by the revenue-sharing contract parameters were (0.72, 0.58), (0.72, 0.66), and (0.77, 0.58). By selecting any combinations of ϕ_{A} and ϕ_{B} within the acceptable range, the optimization of the expected profit of the entire supply chain as well as each party could be realized.

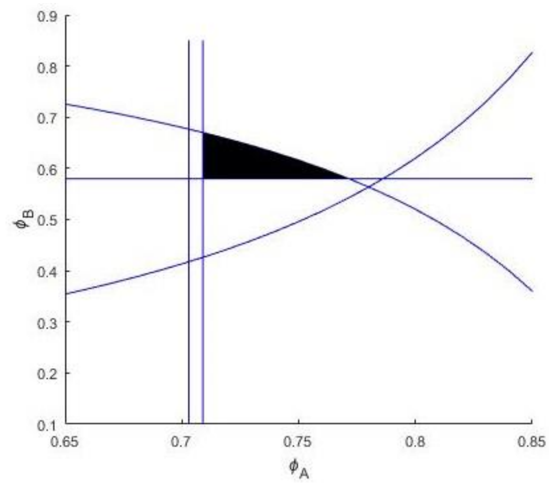

Fig. 2. Acceptable range of the revenue-sharing coefficient

Changes in the Expected Profit of Each Member under Different Revenue-sharing Contract Parameters

Within the acceptable range of the revenue-sharing coefficients, several combinations of ϕ_A and ϕ_B were evenly selected to obtain the expected profit of each party in the reverse supply chain under the revenue-sharing contract. By comparing the variations in expected profit, the increment of expected profit under the revenue-sharing contract compared to that under the traditional wholesale price mode could be obtained. The results are summarized in Table 4. Within the acceptable range of revenue-sharing coefficients, any combinations of ϕ_A and ϕ_B could help the three parties increase their profits and realize the coordination of the reverse supply chain. The increment of each party depended on the value of the revenue-sharing coefficients. When ϕ_A was constant, the increase of ϕ_B led to the profit increase of the third-party recycler. When ϕ_B was constant, the increase of ϕ_A led to the profit increase of the remanufacturer. The shares in the increased revenue of the parties depended mainly on the revenue-sharing coefficients, which were determined by the positions of the parties in the supply chain and the bargaining power they had over one another.

Table 4. Variations in Expected Profit of Each Party under Different Combinations of Revenue-sharing Coefficients

Revenue-sharing Coefficients	Profit of Remanufacturer (US$/10,000 bags)	Increment Compared to Wholesale Mode	Profit of Recycler (US$/ 10,000 bags)	Increment Compared to Wholesale Mode	Profit of Wood Processing Mill (US$/ 10,000 bags)	Increment Compared to Wholesale Mode
(ϕ_A, ϕ_B)	Π_{Rc}	$\frac{\Pi_{Rc}-\Pi_{Rm}}{\Pi_{Rm}}$	Π_{Dc}	$\frac{\Pi_{Dc}-\Pi_{Dm}}{\Pi_{Dm}}$	Π_{Mc}	$\frac{\Pi_{Mc}-\Pi_{Mm}}{\Pi_{Mm}}$
(0.74, 0.62)	238,650	5.08%	51,987	27.92%	31,863	0.80%
(0.74, 0.58)	238,650	5.08%	48,633	19.67%	35,217	11.42%
(0.75, 0.60)	241,875	6.50%	48,375	19.03%	32,250	2.03%
(0.75, 0.58)	241,875	6.50%	46,763	15.06%	33,863	7.13%
(0.76, 0.59)	245,100	7.92%	45,666	12.38%	31,734	0.40%
(0.76, 0.58)	245,100	7.92%	44,892	10.46%	32,508	2.84%

CONCLUSIONS

1. A revenue-sharing contract can effectively adjust the three-echelon reverse supply chain of wood-processing residue and realize profit maximization for each party. In the studied case, the expected profit of the reverse supply chain with a revenue-sharing contract was greater than that under the traditional wholesale price mode under certain conditions. The result was consistent with the findings in Zhu *et al*. (2016). They analyzed the expected profits of a three-echelon supply chain based on revenue-sharing contracts under centralized decision-making and proved the effectiveness of revenue-sharing coordination.
2. Within the acceptable range of revenue-sharing coefficients in the three-echelon reverse supply chain, the implementation of a revenue-sharing contract can lead to a certain decrease in sales price of the fungus product compared to the traditional wholesale price mode. However, the price decrease led to an increase in market demand for the product, and the expected profits of the entire supply chain and the related parties were improved. Compared with a two-echelon reverse supply chain, there may be some challenges such as escalating administrative cost and coordination difficulties while adopting three-echelon reverse supply chain in practice. Our study results showed that both supply chains would have the same expected profits under centralized decision-making given the same recycling cost. With the increase of recycling cost in the two-echelon supply chain, the expected profits would decrease, making the two-echelon supply chain less competitive than the three-echelon supply chain.
3. Even though the expected profits of all the parties in the three-echelon reverse supply chain can be improved within the acceptable range of revenue-sharing coefficients, the shares of the parties in the increased revenue depend mainly on the revenue-sharing coefficients. According to the coordination mechanism, the revenue-sharing coefficient between the remanufacturer and the third-party recycler ranged from 0.72 to 0.77, and that between the recycler and the wood-processing mill ranged from 0.58 to 0.66. The specific revenue-sharing coefficients were determined by the positions of the parties in the reverse supply chain and their bargaining power.
4. Revenue-sharing is a valuable strategy in coordinating the profit distribution among different members of the three-echelon reverse supply chain. However, there are also some limitations in this study. The information in the reverse supply chain was assumed to be completely symmetrical, the demand on the remanufactured product was a deterministic price-sensitive demand, and stockout loss cost was not considered. Future research should be conducted to achieve the goal of coordination and win-win situations for the upstream and downstream members of the three-echelon reverse supply chain under asymmetric information and take stockout loss cost and more complex market demand into consideration.

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