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Modeling and identification of suitable motivational mechanism in the collection system of municipal solid waste supply chain

Pradeep Rathore [a,*], S.P. Sarmah [b]

[a] Symbiosis Centre for Management Studies (SCMS), Nagpur (Constituent of Symbiosis International Deemed University, Pune), Nagpur 440008, Maharashtra, India
[b] Department of Industrial and Systems Engineering Indian Institute of Technology, Kharagpur 721302, India

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ABSTRACT

Many studies have identified that incentive, subsidy, and reward-penalty mechanisms improve the collection rate of recyclables and end of life products. But there is a lack of studies mathematical models and analysis of these mechanisms in the context of municipal solid waste supply chain. Therefore, in this study, models have been formulated for municipal solid waste supply chain (profit) considering government and collectors' profit under incentive, subsidy, and reward-penalty mechanisms. The study has analysed the models against the non-separation and separation scenario of waste. A numerical analysis is performed and observed that: (*i*) separation of waste at source along with incentive, subsidy, and reward-penalty mechanisms scenario improve the collection rate by 17%, 23%, 30%, and 45% compared to non-separated MSW. (*ii*) Incentive, subsidy, and reward-penalty mechanisms increases the total supply chain profit by around 9%, −36% and 18%. (*iii*) reward-penalty mechanism performs better than incentive and subsidy mechanism by providing the high supply chain profit (18% and 85%) and collection rate (22% and 15%) comparatively. Further, sensitivity analysis carried out to understand the behaviour of the models against the key parameters. The study also develops interesting propositions and proved for a better understanding of the models. From results, some key managerial insights have been drawn and a few future scopes of the study are presented.

1. Introduction

The development of landfills and the accumulation of garbage in the society is one of the most concerning issues around the globe (Hemmelmayr et al., 2013; Samadder et al., 2017). Both creates soil (Tauqeer et al., 2021a, 2021b), air (Iftikhar et al., 2021), water (Rasool et al., 2021) and land pollution (Lavee and Nardie, 2013); provide a suitable environment for an epidemic like malaria, cholera, etc.; and also pose threat to the plantation of crops nearby (Pujara et al., 2019; Tauqeer et al., 2021a, 2021b). For instance, heavy metal waste like Nickel (Turan, 2019), cement waste (Naeem et al., 2021), Lead (Turan, 2020), etc. pollute the soil and deteriorate plant quality which causes critical health issues to humans and animals (Turan, 2019). Moreover, landfilling of waste like biowaste worsen the stability of the landfill and damage the environment by producing excess amount of greenhouse gases (Maroušek et al., 2020a, 2020b). Also, this landfilling system incurred huge cost to local authorities. The major reason for this situation is improper collection and non-separation of waste in municipal solid waste supply chain (MSWSC) (Khan and Samadder, 2016). Non-separation of municipal solid waste (MSW) at source reduces the quality of MSW and makes it uneconomical for further processing (composting, recycling, remanufacturing, and waste to energy) (Wilson and Cannon, 2015). Therefore, non-separated MSW mostly ends in landfills. While the improper collection leads to the littering of MSW and causes accretion of garbage at various places inside the city (Gupta et al., 2015). Thus, it can be inferred that for a proper MSW management (MSWM) an efficient MSWSC is required.

The efficiency of an MSWSC mostly depends on its collection rate and disposal methods (landfill, recycling, composting, remanufacturing, and waste to energy) (Xu et al. 2017). The MSWSC of middle and low-income countries are considered as inefficient due to improper collection and disposal method. In low-income countries (Ghana, Ethiopia, etc.) collection rate is below 50%, whereas, in middle-income countries (India, Thailand, etc.) it varies between 50 and 80% (Hoornweg and Bhada-Tata, 2012). Moreover, from this collected MSW, only 40% is transferred to processing plants while the remaining 60% is sent to landfills (Wilson and Cannon, 2015; Rathore and Sarmah, 2021). Therefore,

* Corresponding author.
E-mail addresses: pradeeprathore076@gmail.com (P. Rathore), spsarmah@iem.iitkgp.ac.in (S.P. Sarmah).

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nowadays, local authorities of low and middle-income countries are hiring third parties (collector) for the collection and disposal of MSW (Ranjith Kharvel Annepu, 2012). For example, in India, local authorities of many cities have already given the responsibility of collection and disposal of MSW to various collectors under public–private partnership (PPP) policy (MoEF, 2010).

Apart from this, due to the continuous degradation of environmental conditions, researchers have been suggesting for moving towards the green supply chain (GSC). Shivastava (2007) presented a literature review of GSC application in various research areas like manufacturing, logistics, and waste management. Moreover, from the past few years, many world-known organizations are trying to make their supply chain greener. For example, fast fashion industries (H&M, Zara, Mango, C&A, etc.) have already taken steps towards the GSC by reducing pollution and energy consumption (Turker and Altuntas, 2014). Similarly, Xerox, Canon, Kodak, Dell, and Acer have also made efforts towards GSC. For instance, Xerox, able to reduced 42% emissions and 31% energy consumptions for making their supply chain greener (Xerox, 2017). Thus, it can be inferred that for making the MSWSC greener, a reduction in pollution and energy is required. As mentioned before, in MSWSC, landfills and uncollected MSW are the major sources of pollution (Pujara et al., 2019). Therefore, a reduction in the quantity of MSW ending in landfills and improving the collection rate can be a huge step towards MSW GSC.

Meanwhile, many researchers have demonstrated, separation of MSW at source and its collection increases the composting, recycling, remanufacturing, and waste to energy of MSW (Jena and Sarmah, 2015; Xu et al., 2017; Wang et al., 2019a). It is also considered method like recycling can reduce the direct cost of municipalities (Lavee, 2007). Further, this results in a reduction of MSW ending in landfills. In addition, empirical studies have identified that incentive, subsidy, and reward-penalty (RPM) mechanisms motivate the people for submitting their MSW to the collector (Chen and Ulya, 2019; Matter et al., 2015; Wang et al., 2017). Also, there are studies that suggest economic tools are effective in managing the environmental issues (Lavee, 2020). But, till now, no study has mathematically modelled and analysed these mechanisms for MSWSC for non-separation and separation of MSW scenario. Also, best to our knowledge till now no study has considered the government and collectors profit together for calculating the collection rate and MSWSC profit. In addition, comparison of incentive, subsidy, and RPM mechanisms based on government, collectors, and supply chain profit is also absent in literature. All these gaps restrict the analysis of MSWSC for various scenarios and strategies. Without mathematical model it is hard to compare different scenarios and to identify that how much they impact the MSWSC. Further, from mathematical analysis it is easy to evaluate the contribution of every entity in the supply chain. These issues have motivated us for this study. Therefore, in this study, mathematical models of incentive, subsidy, and RPM mechanisms are developed and analysed for non-separation and separation of MSW scenario. Moreover, the impact of proposed mechanisms over the collection rate and profit of MSWSC are tested for both scenarios. Also, for MSWSC, government and collector profits are considered in the model. Along with these novelties, the study answers the following questions.

(RQ1) How separation of MSW at the source scenario is better than non-separation scenario in MSWSC?

(RQ2) How incentive, subsidy, and RPM mechanism impact the collection rate and profit of MSWSC, and which mechanism has the most impact?

(RQ3) How do different situations impact the performance of the mechanisms?

Answers of the above research questions will help the countries to choose between separation and non-separation of MSW at source. They assist the local authorities in selection of the best suitable mechanisms as per their conditions. Also, it helps in selection of third private parties for collection of MSW.

The rest of the paper is organized as follows. The literature review is presented in Section 2. Section 3 describes the problem. Mathematical models are presented in Section 4. In Section 5, propositions developed in the study are discussed. Section 6 contains the numerical analysis along with the result, discussion, and sensitivity analysis. Managerial implications of the study are listed down in Section 7, and the conclusion and future research directions are made in Section 8.

2. Literature review

There is a dearth of literature on the analysis of the impact of mechanisms (incentive, subsidy, and reward-penalty) on the MSWSC collection rate considering separation and non-separation scenario of waste. But there are many studies available on the analysis of these mechanisms for open and closed-loop supply chain (CLSC) of recycling and remanufacturing (Shen et al., 2018). Therefore, the review has been restricted here only to the articles on the impact of incentive, subsidy, and reward-penalty mechanism in recycling and remanufacturing supply chain.

Savaskan et al. (2004), developed a model for product remanufacturing. They investigated the impact of reverse channel or CLSC over the forward channel supply chain. They derived mathematical equations that proves CLSC reduces the manufacturing cost and increases the manufacturer's profit. Mukhopadhyay and Setaputra (2006), proposed the use of fourth-party logistics (4PL) as a return service provider. They identified the conditions under which both seller and 4PL can increase the profit. Afterward, Harder and Woodard (2007) studied the influence of shop and leisure voucher incentives for household recycling. They observed a 20% increase in the return of recyclables. Li and Xiao (2010), developed a model for incentive-penalty contract considering linear demand-quality in the supply chain. They observed that incentive-penalty can achieve coordination among the supply chain members. Apart from the incentive, another mechanism such as government subsidy has also been studied. It was identified that subsidy boosts the remanufacturing activity and the profit of the remanufacturer when 100% subsidy goes to remanufacturer (Mitra and Webster, 2008). Aksen et al. (2009), developed a mathematical model for the government-subsidised collection system, where, collection company provides an incentive to customers to boost their willingness to return of used products. They identified that with the increase in subsidy collection rate also increases and thus a high subsidy gives a high collection rate. Similarly, Shi and Min (2013), investigated the collection rate of recyclables in centralised, decentralised, and the government-subsidised decentralized CLSC. From the analysis, it is observed that the collection rate during the centralized system is more than the decentralised CLSC. Again, within the decentralized CLSC, the government-subsidised CLSC performs better. In their analysis, they also investigated the non-recycling and recycling scenario. It was found that recycling brings more profit because, in non-recycling, most of the recyclables end up in the landfill. Later, Hong et al. (2014), analysed the interaction of government subsidy and recycling fee with recycling and disposal of end-of-life products. Their result suggested, a balance between subsidy and fee can achieve the maximum social welfare in the supply chain. Das and Dutta (2015), investigated the impact of promotional offers for the recovery of the used products from consumer. They found that in presence of promotional offers, recovery rate increases upto 70% and thus the profit of the supply chain increases around 30%. Further, Xu et al. (2015) proposed a framework of incentive-based source separation model for sustainable waste management in China. Wang et al. (2015) studied the influence of RPM used by the government for returning of waste electrical and electronic products. They analysed both manufacturer-led and collector-led scenarios along with on and off government intervention. Their analysis proved that the increase in the RPM values improve the collection rate and lower the product price. Later, Wang et al. (2017) also investigated the effect of government intervention through RPM on information screening contracts in asymmetric CLSC. In the study, it is observed, RPM increases the collection quantity by around 40%. Again, Wang et al. (2018) extended their study by analysing the impact of RPM over two-period CLSC. Their study demonstrated that RPM has greater influence over manufacturers in two-period CLSC compared to a single period. Further, Tang et al. (2019), formulated a mathematical model for testing both subsidy and RPM in the recycling of EV batteries. It is found that RPM enhances the recycling rate nearly by 2% more than the subsidy. Meanwhile, Chen and Ulya (2019), investigated the implementation of RPM by the government in green CLSC. For the analyses, they developed the mathematical models considering the profits of manufacture, retailer, and collector. It is observed that RPM increases the return rate of used products and green effort by the collector.

From the literature review, it can be observed that researchers have made a strong contribution to the field of development of the mathematical model for recycling and remanufacturing supply chain. They have also compared the various mechanisms by analysing their impact on profits and return rates. But till now, there is no mathematical model and analysis of such mechanisms (incentive, subsidy, and RPM) for MSWSC which is a clear gap in the literature. Moreover, from literature it can also be observed that no study has considered government as well as collectors profit in MSWSC profit model. Therefore, in this study, mathematical models have been developed for incentive, subsidy, and RPM mechanism in separation and non-separation scenario of the MSW. Moreover, the presented study has also considered both government and collectors profit in MSWSC profit model. Thus, the proposed study fulfils the identified gaps in the literature and made its contribution.

3. Background of the model and methods

Here, the model description and key assumptions are presented. Afterward, various supply chain models are developed, and their corresponding solutions are derived.

3.1. Model description

Two scenarios have been considered in this study as shown in Fig. 1 and Fig. 2 respectively. In the figures, solid lines are showing the flow of product and MSW while the dotted lines are showing the cash flow. Fig. 1 shows the non-separation scenario of MSWSC which is the current practice of cities in many low and middle-income countries. In this scenario, the household buys products from the market by paying the market price (P) and government tax (θ). Consumption of the product generates MSW ($\gamma * D$). The generated MSW is collected at a collection rate (τ) by a third-party collector. For this collection process, the government pays the tipping fee (h) to the collector. Meanwhile, the household also pays the collection fee (K) to the collector ($h >> K$) (Kumar and Nandini, 2013). As the collected MSW are mixed or not separated, they are sent to landfill.

Fig. 2 shows the proposed MSWSC considering the separation of MSW at the source scenario. Comparing with Fig. 1, one can observe that in the proposed MSWSC, the market is selling both manufactured and remanufactured/recycled products at price P and P_r respectively. In this system, instead of sending the MSW on landfills, the collector is selling the separated MSW to processing plants (remanufacturer, recycler, composting plant, etc.) at price (ψ) where $\psi << P, P_r$ (Dutta et al., 2016). From the processing plant, products again go to consumers and thus form a CLSC. As the MSW is not ended up in the landfill, it will reduce pollution from MSWSC and makes it greener.

The notation used in the development of the models is presented in Table 1 and the assumptions are described in subsection 3.2.

3.2. Model assumptions

Following are the assumptions considered in the development of the model:

The production of remanufactured/recycled products are very less compared to the production of manufactured products. Therefore, both types are having different demands in the market ($D_S \neq D_r$). In addition, demand uncertainty is considered as barrier for the firms therefore the demand is considered to be deterministic (Lavee and Regev, 2020).

As the cost of remanufacturing/recycling is lower than the manufacturing (Savaskan et al., 2004; Chen and Chang, 2012) therefore, it has been assumed, market price or selling price of remanufac-

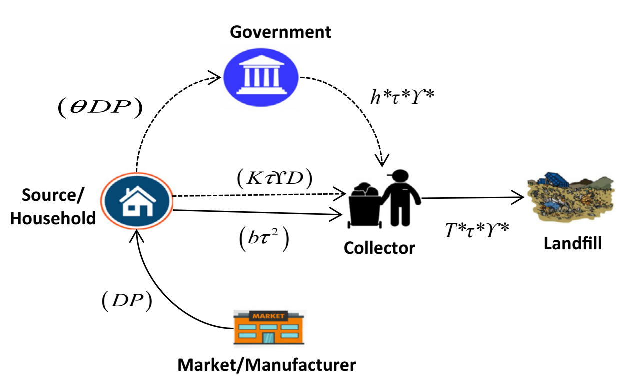

Fig. 1. Non-separation MSW collection system with supply chain entities (Household, Government, Collector, Landfill, and Manufacturer), and their cost and revenues.

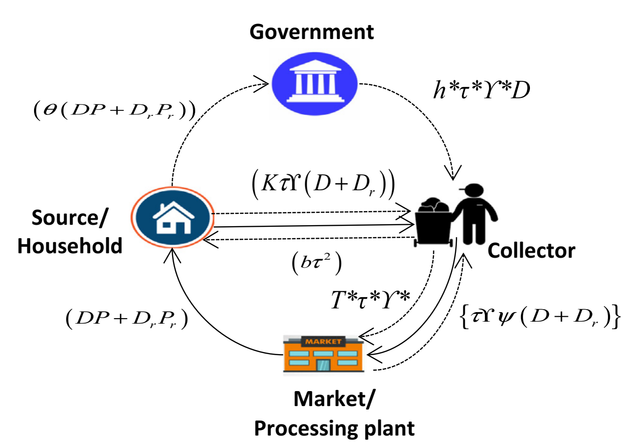

Fig. 2. Separated MSW collection system with closed loop supply chain entities (Household, Government, Collector, Landfill, and Manufacturer), and their cost and revenues.

Table 1
Notation with description used in the models.

Notations	Description
Indexes	
i	Supply chain entity
j	Scenario
Parameter	
D_{NS}	Demand of manufactured product in non-separation of MSW scenario
D_S	Demand of manufactured product in separation of MSW scenario
D_r	Demand of recycled product in separation of MSW scenario
P	Market price of the manufactured product (Rs. /unit)
P_r	Market selling price of the recycled product (Rs. /unit)
θ	Tax on the selling of product (%)
β	Tax on selling of MSW (%)
Υ	Fraction of products converted into waste (%)
τ_0	Target collection rate (%)
h	Tipping fee (Rs. /unit)
T	Transportation cost (Rs. /unit)
b	Scaler parameter
K	Collection fee (Rs. /unit)
Ψ	Selling price of MSW (Rs. /unit)
U	Social cost for uncollected waste (Rs. /unit)
μ	Incentive or discount provided to source by collector (Rs. /unit)
ω	Reward-penalty (Rs. /unit)
α	RPM share ratio (%)
σ	Government subsidy on selling price of recycled products (%).
ϕ	Tax on fuel (%).
ε	Increment in selling price of MSW due to incentive (Rs. /unit)
Derived functions	
Π_j^i	Profit function of supply chain entity (i) at scenario (j)
G	Government
C	Waste collector
Decision variable	
τ_j	Collection rate at scenario (j) (%).

tured/recycled products is less than the manufactured products ($P > P_r$).

In MSWSC, the collection of MSW depends upon the awareness level of the sources and facilities. As the collector is responsible for the collection and disposal of MSW, it is assumed, the collector will invest an amount (I) to enhance the awareness of the households (e.g., through advertisement, educational campaign, etc.) towards solid waste. I is a function of τ and it is expressed as $I = b\tau^2$, where, b is a scale parameter of separated MSW (b > 0) (Wang et al., 2015).

The number of variations in manufactured goods is enormous. Thus, the variety of remanufactured/recycled products will also be very high. It is very difficult to impose different taxes as per the variety of manufactured/recyclable products. Therefore, to reduce the complexity of taxation, it is considered, the government imposes the same tax on the selling of manufactured and remanufactured/recycled products.

The consumption of products will remain the same in all scenarios. So, the total demand of the product will be constant in all the scenarios i.e.,$D_{NS} = D_S + D_r$

Take back cost is the same for all types of separated MSW. Because, there are various types of waste (glass, paper, cardboard, packaging, plastic, cloth, etc.) and it is difficult to consider the selling price of all the waste.

As the uncollected MSW pollutes the city, local governments are responsible for maintaining sanitation. As a result, the government is responsible for a social cost (U) (Wang et al., 2015; Chen et al., 2018). The government would be motivated to press collectors for a high collection rate as a result of this.

4. Mathematical models

This section describes the mathematical models developed for MSWSC under the non-separation and separation scenarios of MSW at the source. It also describes the MSWSC models for incentive, subsidy, and RPM mechanism considering MSW separation at source.

4.1. Non-separated MSWSC scenario

This scenario is very common in many low and middle-income countries where households do not separate their MSW and it is disposed of to landfills (see Fig. 1). The profit function of the government, collector, and MSWSC in this scenario is described as follows.

The profit function of the government is written as

$$\max_{\tau_{NS}} \Pi_{NS}^G = \theta D_{NS} P - h\tau_{NS}\gamma D_{NS} - U(1-\tau_{NS})\gamma D_{NS}$$
$$s.t\ \theta \leqslant 1;\ \tau_{NS}, \gamma \leqslant 1 \qquad (1)$$
$$\theta, D_{NS}, P, h, \tau_{NS}, \gamma, U, C_{PM} \geqslant 0$$

$$\max_{\tau_{NS}} \Pi_{NS}^C = (h-T)\tau_{NS}\gamma D_{NS} + K\tau_{NS}\gamma D_{NS} - b\tau_{NS}^2$$
$$s.t\ T \leqslant h;\ \gamma \leqslant 1;\ K \leqslant P;\ \tau_{NS} \leqslant 1 \qquad (2)$$
$$D_{NS}, T, h, \tau_{NS}, \gamma, K \geqslant 0$$

Here, the first term denotes the earning of the collector (h-T) from the government for the collection of MSW ($\tau_{NS}\gamma D_{NS}$); the second term presents the earning of the collector from collection fee (K) paid by the households for collection of MSW ($\tau_{NS}\gamma D_{NS}$); and the last term shows the investment cost incurred by the collector to aware the households about MSW, use of bins, etc.

The total profit of the MSWSC is the summation of the profit of government and collector together. Therefore, the profit function of the MSWSC can be written as follows.

$$\max_{\tau_{NS}} \Pi_{NS} = \Pi_{NS}^G + \Pi_{NS}^C$$
$$= \theta D_{NS} P + K\tau_{NS}\gamma D_{NS} - T\gamma D_{NS}\tau_{NS} - U(1-\tau_{NS})\gamma D_{NS} - b\tau_{NS}^2 \qquad (3)$$

As the collection rate is the only decision variable, the whole MSWSC profit depends on it. Therefore, to maximize the profit, the optimal value of τ_{NS} can be given by

$$\tau_{NS}^* = \frac{\gamma D_{NS}(K+U-T)}{2b}$$

4.2. Separation of MSW (Closed-loop supply chain) scenario

In this scenario, both manufactured (D_S) and remanufactured/recycled products (D_r) are sold in the market at selling price (P) and (P_r) respectively. Households separate their generated MSW ($\gamma(D_S + D_r)$) and the collector generates revenue ($\tau_S\gamma\psi(1-\beta)(D_S + D_r)$) by selling the collected MSW to the remanufacturer/recycler. Meanwhile, government revenue from the tax on product selling reduces as ($P > P_r$) and additional revenue ($\tau_S\gamma\psi\beta(D_S + D_r)$) is obtained from tax ($\beta$) on the selling of MSW. As mentioned earlier, this proposed scenario is analysed by considering four different scenarios. The impact of those four scenarios on the collection rate and supply chain profits of CLSC are described below.

4.2.1. Normal scenario

This scenario represents the separation of the MSW scenario, which does not have any additional mechanism to motivate the households and collectors. In this scenario, it is assumed that households and collectors are self-motivated towards the separation and collection of MSW. Therefore, the profit function of stakeholders for this scenario can be written as follows.

Government profit:

$$\begin{aligned}\max_{\tau_S} \Pi_S^G &= \theta(D_S P + D_r P_r) + \beta\psi\tau_S\gamma(D_S + D_r)\\ &-h\tau_S\gamma(D_S + D_r) - U(1-\tau_S)\gamma(D_S + D_r)\\ &s.t\ \theta \leqslant 1;\ \tau_S, \gamma, \beta \leqslant 1;\ \psi \leqslant P\\ &\theta, D_S, D_r, P, h, \beta, \tau_S, \gamma, U, \psi \geqslant 0\end{aligned} \tag{4}$$

Collector profit:

$$\begin{aligned}\max_{\tau_S} \Pi_S^C &= (h-T)\tau_S\gamma(D_S + D_r) + K\tau_S\gamma(D_S + D_r)\\ &+\tau_S\gamma\psi(1-\beta)(D_S + D_r) - b\tau_S^2\\ &s.t\ T \leqslant h;\ \gamma, \tau_S, \beta \leqslant 1;\ K, \psi \leqslant P\\ &D_S, D_r, T, h, \tau_S, \gamma, \beta, K, \psi \geqslant 0\end{aligned} \tag{5}$$

The total MSWSC profit:

$$\begin{aligned}\max_{\tau_S} \Pi_S &= \Pi_S^G + \Pi_S^C = \theta(D_S P + D_r P_r) + K\tau_S\gamma(D_S + D_r)\\ &+\tau_S\psi\gamma(D_S + D_r) - T\tau_S\gamma(D_S + D_r)\\ &-U(1-\tau_S)\gamma(D_S + D_r) - b\tau_S^2\end{aligned} \tag{6}$$

The optimal τ_S for this supply chain is obtained as follows.

$$\tau_S^* = \frac{\gamma(D_S + D_r)(K - T + U + \psi)}{2b}$$

4.2.2. Incentive mechanism for MSWSC in the separation of MSW scenario

In this scenario, it is considered that households are not fully motivated towards the separation of MSW. The collector is providing some discount or incentive (μ) in the collection fee (K) ($\mu \leqslant K$) to motivate the households to separate the waste. Providing incentive lowers the profit of the collector. So, for maintaining the economic equilibrium, the collector increases the selling price of MSW (Ψ) by ε (Shi and Min, 2013). Here, from economic equilibrium, we mean that financial loss due to incentive is covered by the financial gain from the selling of MSW to recycler/remanufacturer so that collector remains financially in equilibrium. The increase in the selling price of MSW consequently increases the tax revenue of the government ($\beta(\psi+\varepsilon)\tau_{SI}\gamma(D_S + D_r)$). Thus, the incentive mechanism transforms the profit functions of the CLSC scenario into the following equations.

Government profit

$$\begin{aligned}\max_{\tau_{SI}} \Pi_{SI}^G &= \theta(D_S P + D_r P_r) + \beta(\psi+\varepsilon)\tau_{SI}\gamma(D_S + D_r)\\ &-h\tau_{SI}\gamma(D_S + D_r) - U(1-\tau_{SI})\gamma(D_S + D_r)\\ &s.t\ \theta \leqslant 1;\ \tau_{SI}, \gamma, \beta \leqslant 1;\ \psi, \varepsilon \leqslant P\\ &\theta, D_S, D_r, P, h, \beta, \tau_{SI}, \gamma, U, \psi, \varepsilon \geqslant 0\end{aligned} \tag{7}$$

Collector profit

$$\begin{aligned}\max_{\tau_{SI}} \Pi_{SI}^C &= (h-T)\tau_{SI}\gamma(D_S + D_r) + (K-\mu)\tau_{SI}\gamma(D_S + D_r)\\ &+\tau_{SI}\gamma(\psi+\varepsilon)(1-\beta)(D_S + D_r) - b\tau_{SI}^2\\ &s.t\ T \leqslant h;\ \gamma, \tau_{SI}, \beta \leqslant 1;\ K, \psi, \varepsilon, \mu \leqslant P\\ &D_S, D_r, T, h, \tau_{SI}, \gamma, \beta, K, \psi, \mu \geqslant 0\end{aligned} \tag{8}$$

Total MSWSC profit

$$\begin{aligned}\max_{\tau_{SI}} \Pi_{SI} &= \Pi_{SI}^G + \Pi_{SI}^C = \theta(D_S P + D_r P_r)\\ &+(K-\mu)\tau_{SI}\gamma(D_S + D_r) + \tau_{SI}(\psi+\varepsilon)\gamma(D_S + D_r)\\ &-T\tau_{SI}\gamma(D_S + D_r) - U(1-\tau_{SI})\gamma(D_S + D_r) - b\tau_{SI}^2\end{aligned} \tag{9}$$

The optimal τ_{SI} for this supply chain is:

$$\tau_{SI}^* = \frac{(D_S + D_r)\gamma(K - T + U - \mu + \psi + \varepsilon)}{2b}$$

4.2.3. Government subsidy mechanism in the separation of MSW scenario

In this scenario, to motivate the households towards the separation of waste at source and recycling, the government provides subsidy (σ) in the market price (P_r) of remanufactured/recycled products (Heydari et al., 2017). Also, to maintain the financial equilibrium the government raises the fuel taxes by ϕ on existing fuel prices (Srivastava et al., 2003; Shi and Min 2013). Increment in fuel price ($T(1+\phi)$), increases the transportation cost of the collector ϕT. As the collector is a private party and does not compromise on the profit (Zheng et al., 2017), the collector will raise the tipping fee ($h \to h_{SS}$) so that it attains the financial equilibrium. Thus, it can be represented as financial loss to the government due to subsidy and is equivalent to gain from the transportation cost of the collector (Shi and Min, 2014) ($\theta\sigma D_r P_r = T(1+\phi)\gamma(D_S + D_r)$). Therefore, considering the scenario, the profit functions, and collection rate will transform into the following equations.

Government profit

$$\begin{aligned}\max_{\tau_{SS}} \Pi_{SS}^G &= \theta(D_S P + (1-\sigma)D_r P_r) + \beta\psi\tau_{SS}\gamma(D_S + D_r)\\ &-h_{SS}\tau_{SS}\gamma(D_S + D_r) - U(1-\tau_{SS})\gamma(D_S + D_r)\\ &s.t\ \theta \leqslant 1;\ \tau_{SS}, \gamma, \beta, \sigma \leqslant 1;\ \psi, \varepsilon \leqslant P\\ &\theta, D_S, D_r, P, h_{SS}, \beta, \tau_{SS}, \gamma, U, \psi, \varepsilon \geqslant 0\end{aligned} \tag{10}$$

Collector profit

$$\begin{aligned}\max_{\tau_{SS}} \Pi_{SS}^C &= (h_{SS} - T(1+\phi))\tau_{SS}\gamma(D_S + D_r) + K\tau_{SS}\gamma(D_S + D_r)\\ &+\tau_{SS}\gamma\psi(1-\beta)(D_S + D_r) - b\tau_{SS}^2\\ &s.t\ T \leqslant h_{SS};\ \gamma, \tau_{SS}, \beta, \phi \leqslant 1;\ K, \psi \leqslant P\\ &D_S, D_r, T, h, \tau_{SS}, \gamma, \beta, K, \psi \geqslant 0\end{aligned} \tag{11}$$

Total MSWSC profit is given as follows.

$$\begin{aligned}\max_{\tau_{SS}} \Pi_{SS} &= \Pi_{SS}^G + \Pi_{SS}^C = \theta(D_S P + D_r P_r) - \sigma D_r P_r\\ &+K\tau_{SS}\gamma(D_S + D_r) + \tau_{SS}\gamma\psi(D_S + D_r)\\ &-T(1+\phi)\tau_{SS}\gamma(D_S + D_r) - U(1-\tau_{SS})\gamma(D_S + D_r) - b\tau_{SS}^2\end{aligned} \tag{12}$$

Optimal $\tau_{SS}^* = \frac{\gamma(D_S+D_r)(K+\psi+U-T(1+\phi))}{2b}$ or $\frac{\gamma(D_S+D_r)(K+\psi+U)-\sigma\theta D_r P_r}{2b}$

4.2.4. Reward-penalty mechanism (RPM) in the separation of MSW scenario

This scenario examines the impact of RPM over the collection rate and profit functions of the CLSC scenario. Here, to motivate the collector for a high collection rate, the government sets a target collection rate (τ_0) for the collector. The government provides a condition that if the collector collects MSW more than the set target ($\tau_0 < \tau_{SRPM}$) than, the MSW supply chain will get reward (ω). Otherwise, for collecting less MSW ($\tau_{SRPM} < \tau_0$), penalty (ω) will be imposed. To maintain fairness in the mechanism, both reward and penalty will be shared by the government and collector based on a sharing ratio (α) (C. K. Chen and Ulya, 2019).

Government profit

$$\begin{aligned}\max_{\tau_{SRPM}} \Pi_{SRPM}^G &= \theta(D_S P + D_r P_r) + \alpha\omega(\tau_{SRPM} - \tau_0)\gamma(D_S + D_r)\\ &+\beta\psi\tau_{SRPM}\gamma(D_S + D_r)\\ &-h\tau_{SRPM}\gamma(D_S + D_r) - U(1-\tau_{SRPM})\gamma(D_S + D_r)\\ &s.t\ \theta \leqslant 1;\ \tau_{SRPM}, \tau_0, \gamma, \beta, \alpha \leqslant 1;\ \psi \leqslant P\\ &\theta, D_S, D_r, P, P_r, h, \beta, \tau_{SRPM}, \tau_0, \gamma, U, \psi, \varepsilon \geqslant 0\end{aligned} \tag{13}$$

Collector profit

$$\begin{aligned}\max_{\tau_{SRPM}} \Pi^{C}_{SRPM} &= (h-T)\tau_{SRPM}\gamma(D_S+D_r)\\ &+K\tau_{SRPM}\gamma(D_S+D_r)+\tau_{SRPM}\gamma\psi(1-\beta)(D_S+D_r)\\ &+(1-\alpha)\omega(\tau_{SRPM}-\tau_0)\gamma(D_S+D_r)-b\tau^2_{SRPM}\\ &s.t\ T\leqslant h;\ \gamma,\tau_{SRPM},\tau_0,\beta,\alpha\leqslant 1;\ K,\psi,\omega\leqslant P\\ &D_S,D_r,T,h,\tau_{SRPM},\gamma,\beta,K,\psi,\alpha\geqslant 0\end{aligned} \tag{14}$$

Total MSWSC profit is given as follows.

$$\begin{aligned}\max_{\tau_{SRPM}} \Pi_{SRPM} &= \Pi^{G}_{SRPM}+\Pi^{C}_{SRPM}=\theta(D_SP+D_rP_r)\\ &+\omega(\tau_{SRPM}-\tau_0)\gamma(D_S+D_r)+K\tau_{SRPM}\gamma(D_S+D_r)\\ &+\tau_{SRPM}\psi\gamma(D_S+D_r)-T\tau_{SRPM}\gamma(D_S+D_r)\\ &-U(1-\tau_{SRPM})\gamma(D_S+D_r)-b\tau^2_{SRPM}\end{aligned} \tag{15}$$

$$\tau^*_{SRPM}=\frac{(D_S+D_r)\gamma(K-T+\psi+U+\omega)}{2b}$$

5. Analysis of models

Based on the aforementioned research questions, all the models are compared, to identify the conditions for selecting the best MSWSC as per the situation. The situation and conditions are presented in the form of the following propositions.

Proposition 1. *The total supply chain profit functions Π_S and Π_{NS} are concave in τ_S and τ_{NS}. The optimal solution is given as follows.*

$\tau^*_S=\frac{\gamma(D_S+D_r)(K-T+U+\psi)}{2b}$ and $\tau^*_{NS}=\frac{\gamma D_{NS}(K+U-T)}{2b}$

For proof see Appendix A. From this proposition, it is clear that in both the scenarios (separated MSW and non-separated MSW) there is only one optimal collection rate which will give maximum profit to the supply chain.

Proposition 2. *$\tau_s \geq \tau_{ns}$ always hold for the same parameter values.*

The proof is given in Appendix B. This proposition proves that the separation of MSW is more profitable than non-separation. It also conveys that, if cities, where MSW separation is not in practice, start to separate there and then MSW collection rate will improve.

Proposition 3. *The profit function of supply chains Π_{SI}, Π_{SS} and Π_{SRPM} are concave with respect to τ_{SI}, τ_{SS} and τ_{SRPM}. The optimal solutions are:*

$\tau^*_{SI}=\frac{(D_S+D_r)\gamma(K-T+U-\mu+\psi+\varepsilon)}{2b}$, $\tau^*_{SS}=\frac{\gamma(D_S+D_r)(K+\psi+U)-\sigma\theta D_rP_r}{2b}$ and $\tau^*_{SRPM}=\frac{(D_S+D_r)\gamma(K-T+\psi+U+\omega)}{2b}$

The proof is presented in Appendix C. The proposition shows that all the mechanisms have only one optimal collection rate. Thus, based on the collection rate and supply chain profit, it can be identified which mechanism is having the highest collection rate and maximum profit.

Proposition 4. *For the same parameter values,* $\tau_{SI}>\tau_S, \tau_{SS}>\tau_S$ and $\tau_{SRPM}>\tau_S$ *if $\mu<\varepsilon$, $\sigma>\frac{T}{\theta D_rP_r}$ and $\omega>0$.*

The proof is given in Appendix D. These results help decision-makers in setting the values of incentives, subsidies, and penalties.

Proposition 5. *For the same collection rate (τ), $\Pi_{SI}>\Pi_S$ if $\mu<\varepsilon$.*

The proof is presented in Appendix E. This proposition provides the condition for deciding the value of the incentive. It can also be used to check whether the implementation of an incentive mechanism over the separated MSW system will be profitable or not if the collection rate remains the same.

Proposition 6. *For the same collection rate (τ), $\Pi_{SS}>\Pi_S$ if $\sigma<\frac{T\phi\tau\gamma(D_S+D_r)}{D_rP_r}$.*

For proof see Appendix F. This proposition provides the condition for which subsidy given supply chain performs better than normal CLSC considering the same collection rate. This proposition will help in the calculation of the optimal value of the subsidy.

Proposition 7. *$\Pi_{SRPM}>\Pi_S$ for the same collection rate (τ) only if $\tau>\tau_0$.*

The proof is presented in Appendix G. From this proposition, it is clear that RPM performs better than normal CLSC only if the supply chain collection rate exceeds the target collection rate. It does not depend directly on the values of the penalty or reward. However, from the RPM mechanism, it can be observed that the collection rate directly depends on the penalty/reward.

Proposition 8. *For the same collection rate (τ) $\Pi_{SS}>\Pi_{SI}$ if $\sigma<\frac{(\mu-\varepsilon-T\phi)(D_S+D_r)\tau\gamma}{D_rP_r}$.*

See Appendix H for proof. This proposition helps in deciding between incentive and subsidy mechanism. It shows that if the government provides a subsidy less than the derived condition than the supply chain with subsidy gives more profit than the supply chain with incentive mechanism.

Proposition 9. *For the same collection rate (τ), $\Pi_{SS}>\Pi_{SRPM}$ if $\sigma<\frac{(\omega(\tau_0-\tau)-T\phi\tau)\gamma(D_S+D_r)}{D_rP_r}$.*

The proof is given in Appendix I. This proposition shows the comparison between the subsidy mechanism, and RPM. It explains that if the government subsidy is less than $\frac{(\omega(\tau_0-\tau)-T\phi\tau)\gamma(D_S+D_r)}{D_rP_r}$, then, the government subsidy mechanism is more efficient than RPM. In another way, it can also be said that if the government wants to apply the RPM mechanism over subsidy, then they can calculate the value of reward or penalty and target collection rate from the above condition.

Proposition 10. *For the same collection rate $(\tau)\Pi_{SI}>\Pi_{SRPM}$ if $\mu<\{\varepsilon-\omega(1-\frac{\tau_0}{\tau})\}$.*

The proof is given in Appendix J. This proposition makes the comparison between incentive and RPM profit supply chain. It gives information about the setting of the incentive rate so that the incentive mechanism earns more profit than RPM.

6. Numerical example

MSW consists of various types of waste. Therefore, to test the validity of the developed models, a numerical analysis is performed considering plastic water bottles as the product. For understanding and visualization of the scenarios, city Bilaspur, India has been considered. Presently, the city is practicing non-separation of MSW and want to implement the MSW separation with the help of public–private partnership (PPP) (Planning Commission, 2014). In the city, the average number of persons per household is around 5 and it has been considered that each person consumes a minimum of 4 bottles of one litre each day (Shaban and Sharma, 2007). Collection frequency is 1 week; therefore, demand has been considered weekly. Remaining parameter values have been taken from the city municipality and previous literature (Pearce, 2003; Welivita et al., 2015; Wang et al., 2015; CPHEEO, 2016; Gupta et al., 2015). The values of parameters are presented in Appendix Table I and the results are shown in Table 2.

From Table 2, values of collection rate and profit of government, collector, and total supply chain at non-separated MSW and separated MSW under different scenarios (normal, incentive, subsidy, and RPM) can be observed. Variations in the values show that the scenarios are significantly different from each other and having an impact on the system for the same value of parameters. From the results (see Table 3), it can be mentioned that separated MSW scenarios improve the collection rate by 17%, 23%, 30%, and 45% compared to non-separated MSW. This suggests that the separation of MSW is better for the environment compared to non-separation because the high collection rate leads to less amount of dumps (Rathore and Sarmah, 2020). However, from a profit perspective, government profit (39, −98, −76, −244, and − 149) in the non-separation of MSW is more beneficial compared to the separation of MSW. This is happening because, in the non-separation scenario, the collection rate is low, resulting in a less tipping charge to the collector. On the other hand, in the separated scenario, the collection rate is high and thus high tipping charge. From Table 2, it can be seen that the value of the tipping fee is very high compared to other values and it is dominating the situation. Another reason is, here, costs related to pollution emission and maintenance costs of landfills are not taken into consideration which is causing huge loss to governments and MSWSC of any low and middle-income country. Similarly, as per the collector profits (318, 455, 466, 473, and 573), all separated MSW scenarios along with the mechanisms are more profitable than non-separated MSW scenario; and based on total supply chain profit (357, 357, 390, 229, and 424), except subsidy, remaining scenarios (normal, incentive, and subsidy) are more profitable or equivalent to non-separation of MSW scenario.

The reason for the high collector profit in the separated MSW scenario compared to non-separation is the collection rate. Due to the high collection rate, the collector gets a high collection charge from the government. From Table 3, it can be observed that the scenario with a high collection rate is having higher collector profit. Finally, from the results, it can be inferred that for government, the non-separation scenario is most profitable; for the collector, RPM is most preferable; for MSWSC, RPM is most suitable; and, for collection rate also RPM is the best among all. As the focus of the study is to improve the collection rate and MSWSC profit, therefore based on results, RPM is the best mechanism among all the mechanisms. These results are also in consistent with other studies that have investigated incentive (Xu et al., 2015), subsidy (Wan and Hong, 2019), and reward penalty mechanism (Chen and Ulya, 2019).

6.1. Sensitivity analysis

For strengthening the decision making, sensitivity analysis has been performed (see appendix Fig. I-Fig. VI) considering the parameters such as an incentive (μ), subsidy (σ) and reward/penalty (ω) against the collection rate (τ_{SI}, τ_{SS} and τ_{SRPM}) and all profit functions (government, collector, and MSWSC). In the analysis, the incentive is varied from 0 to 20 Rs. /unit (because incentive cannot be provided more than the market price of the product) and it is observed that incentive and collection rate have a negative linear relationship (see Fig. I). However, the interaction between incentive and profit functions (see Fig. II) shows that government profit is increasing with the incentive; the collector profit is decreasing, and total supply chain profit is first decreased and then it is increased. The reason for this behaviour of profit function is that with the decrease in collection rate (see Fig. I), the total cost of the tipping fee is decreasing. As a result, after a certain level of incentive, government profit has more impact on total MSWSC profit than collector profit. This analysis will help the government to come up with such an incentive mechanism that is fair for everyone and fulfils the desired goal.

Likewise, the impact of subsidy is also analysed and found that the rise in subsidy also decreases the collection rate but marginally (see Fig. III). From Fig. III, it is observed that a total of 90% variation (10–100%) in subsidy decreases the collection rate by only 10%. Similarly, from Fig. IV, it can be identified that variation in subsidy has nearly no impact on profit functions. This is happening because the subsidy is provided on the market price of remanufacture/recycled product which has a very small share in profit. Therefore, variation in market price is not affecting the situation. On the contrary, with the incentive and subsidy, penalty/reward value increases the collection rate significantly (see Fig. V). However, it is interesting to note that even after the increase in the collection rate, MSWSC profit is decreasing (see Fig. VI). The reason for this situation is, with the rise in the collection rate, associated tipping charges are also increasing. This increase in the tipping charge increases the loss of the government which is higher than the increase in profit of the collector and therefore, total profit is decreasing.

7. Managerial implications

This section provides some important managerial insights of this study. From the propositions, results, and sensitivity analysis, it can be observed that the study provides a variety of information that is very helpful for the decision and policy makers of MSW management. Some of the important managerial insights drawn from the study are listed below.

(i) Separation of MSW at the source is beneficial for the collector as well as the supply chain. Therefore, the collector should invest in awareness and motivate the households for the separation of MSW.
(ii) The tipping fee is an important factor; therefore, it is necessary to carefully decide its value. The government and collector should analyse all the situations and estimate the value of the tipping fee such that it satisfies both of them.
(iii) It is necessary to maintain the financial equilibrium whenever any mechanism is implemented or removed from the system.
(iv) Before the implementation of any mechanism, their value should be calculated precisely. So, all the entities of the supply chain should able to cooperate and attain the desired goal.

Table 2
Obtained results of numerical analysis for non-separated, separated, incentive, subsidy, and reward-penalty mechanisms scenarios.

Non-Separated MSW		Separated MSW (CLSC)							
		Normal		Incentive		Subsidy		Reward-penalty	
τ_{NS}	0.39	τ_S	0.56	τ_{SI}	0.62	τ_{SS}	0.69	τ_{SRPM}	0.84
Π^G_{NS}	39	Π^G_S	−98	Π^G_{SI}	−76	Π^G_{SS}	−244	Π^G_{SRPM}	−149
Π^C_{NS}	318	Π^C_S	455	Π^C_{SI}	466	Π^C_{SS}	473	Π^C_{SRPM}	573
Π_{NS}	357	Π_S	357	Π_{SI}	390	Π_{SS}	229	Π_{SRPM}	424

(v) Among the various mechanisms, RPM is the most profitable mechanism for the MSW management system.
(vi) Remanufacturing and recycling industries can identify optimal buy back price according to mechanism (Kliestik et al., 2020).
(vii) Identification of the most suitable mechanism will support the industry towards better implementation of automation for Industry 4.0 (Peters et al., 2020).

8. Conclusion and future research

Pollution caused by landfill and uncollected MSW in society is a serious concern of every local authority. It is suggested, separation of MSW at source and high collection of MSW can help in tackling the problem. Moreover, mechanisms like incentive, subsidy, and RPM also help in improving the collection rate and supply chain profit. Therefore, the study develops the supply chain profit models for government, collector, and MSWSC considering the above mentioned mechanisms. The models are investigated against non-separation and separation of the MSW scenario. A numerical analysis of all the developed models of the scenarios is performed and answers to all the research questions framed. It is found that: (*i*) separation of MSW scenario provide high collection rate and more MSWSC profit than non-separation of MSW scenario; (*ii*) incentive, subsidy, and RPM mechanism increases the collection rate. Moreover, incentive and RPM mechanism also improve the MSWSC profit. In addition, it is also observed that RPM mechanism is having the most impact over collection rate and MSWSC profit. It improves the collection rate by 45% and supply chain profit by around 19% compared to the present scenario; (*iii*) presented models are sensitive to parameter values. Therefore, cities with different input values can have a different scenario. Further, sensitivity is performed considering the parameters such as incentive, subsidy, and reward/penalty against the collection rate and all profit functions (government, collector, and MSWSC). Also, various propositions are developed and proved for better comparison and analysis between the scenarios.

The study can be further explored by incorporating the profit functions of rag-pickers, remanufacturer/recycler, etc. Environmental factors like carbon emission from collection vehicles during forward and reverse supply chains can also be analysed for making the MSWSC greener. Disposal fee can be included to improve the practicality of the model. Moreover, in study economic perspective can be further investigated in order to prevent the bankruptcy (Kliestik et al., 2018). Also, the model can be analysed for different types of products and most suitable mechanism can be identified. Further, analysis can be made on parameters for identifying the ranges for the suitability of the mechanisms. For practical application the remanufacturing process and their associated cost can also be incorporated in the model (Jandačka et al., 2017). Also, the model can be extended for organic and bio waste supply chain (Maroušek et al., 2015) for producing the product biochar (Maroušek et al., 2020a, 2020b).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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