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Advancing Pharmaceutical Waste Management: An Agent-Based Approach to Enhance Consumer Participation in Circular Economy

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09th August 2024

To the Editor-in-Chief Professor Adisa Azapagic PhD

Dear Editor

Please find attached our manuscript entitled 'Advancing Pharmaceutical Waste Management: An Agent-Based Approach to Enhance Consumer Participation in Circular Economy' for consideration at the *Sustainable Production and Consumption.*

We believe that this paper offers a solid contribution to the ongoing conversation within the Journal on understanding the roles and impacts of critical production and consumption systems to advance sustainability at global level. The study explores the role of individual agents and their complex interactions within sustainable consumption systems through Agent-Based Modelling (ABM). From a theoretical point of view, our research expands the number of contributions demonstrating the effectiveness of ABM in modelling complex scenarios such as the circular economy. It also presents, for the first time, empirical evidence on its application in the pharmaceutical industry. Considering practical implications, the developed simulation model can be used as decision support tool to identify the more effective strategy according to the initial population. Starting from the current characteristics of both customers and pharmacists, as well as the localization of collection points, some strategies may therefore result more effective than others. Accordingly, local governments (e.g. regions or cities) can therefore compare different initiatives to be implemented to encourage positive behaviors considering the attitudes of the population, which may vary from one area to another, even within the same country.

With this research, we (i) build on earlier studies and elaborate the proposition of an agent-based model to simulate the customers' behavior on disposal of medications and to evaluate the effectiveness of strategies applied; (ii) offer empirical insights into the pharmaceutical industry, emphasizing the influence of characteristics of the initial population; and (iii) identify the potentiality of the proposed model as decision-support tool.

Having subjected our ideas to valuable peer review, we believe that this paper will have a broad appeal to readers of the *Sustainable Production and Consumption.*

We look forward to hearing from you at your earliest convenience.

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Title Page (with Author Details)

Advancing Pharmaceutical Waste Management: An Agent-Based Approach to Enhance Consumer Participation in Circular Economy

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Abstract

In recent decades, the circular economy paradigm has garnered significant attention as an innovative and sustainable response to the challenges posed by the traditional linear economy. This study emphasizes the pharmaceutical sector, which is critical due to its substantial environmental impact from resource consumption and waste production. Improper disposal of medications results in severe environmental pollution and public health risks, underscoring the importance of effective medication return and disposal systems. However, there are notable limitations in the existing literature. Current research often overlooks the specific complexities and consumer behavior dynamics associated with return management in the pharmaceutical sector. This research aims to address these gaps by employing an Agent-Based Modeling (ABM) approach to simulate consumer behavior regarding the return of expired and unused medications, offering insights into what drives consumer participation in medication return programs. The ABM simulation evaluates various strategies to enhance these programs' effectiveness, such as providing education programs on the environmental risks and social benefits of proper disposal and improving the accessibility of collection points. The study provides practical recommendations to decision-makers for designing more effective return programs considering the initial population, as demonstrated by the implementation of the proposed model in the Italian context. By increasing consumer participation in these programs, the research aims to mitigate the environmental and social impacts associated with improper medication disposal. This study contributes to the literature by offering detailed insights into consumer behavior in the pharmaceutical sector and demonstrating the potential of ABM simulations in optimizing circular economy strategies.

Keywords

Healthcare, Circular Economy, Return Management, Simulation, Agent-Based Modelling, Sustainability

1. Introduction

In recent decades, the paradigm of the circular economy has gained increasing attention as an innovative and sustainable response to the challenges posed by the traditional linear economy. This model, based on a "take, make, dispose" approach of consumption and production, leads to excessive exploitation of natural resources and a significant increase in waste, causing many environmental impacts (Despeisse and Acerbi, 2022). The circular economy, in contrast, promotes a closed system in which materials are continuously reused, repaired, regenerated, and recycled, minimizing waste and the use of virgin resources (Guevara-Rivera et al., 2020). To effectively close the loop, the implementation of circular economy principles need to extend throughout the entire product lifecycle, including the utilization and the collection of post-consumer products (Dragomir and Dumitru, 2024). Consumer attitudes and behaviors, particularly in recycling and returning end-of-life products, largely determine the effectiveness of circular strategies (Dace et al., 2024). The product return phase is critical, as it depends mainly on the end consumer's decisions, especially in the absence of a product-service offer requiring them to return goods after use. Factors influencing consumers' choices to return a product at the end of its useful life to the manufacturer or a collection point strongly impact the effectiveness of circular practices. Understanding consumer decisions regarding product returns and initiatives encouraging virtuous behaviors is crucial for grasping the motivations and dynamics driving these decisions. Additionally, the role of companies, governments, and regulatory bodies is fundamental. They can positively influence consumer behavior through incentives, such as discounts for returning used products, or informational campaigns aimed at raising environmental awareness. Besides, some industries show more criticalities than others in effectively manage return policies, mainly due to intrinsic characteristics of products. The pharmaceutical industry is one of the most significant in terms of resource consumption and waste production (Di Russo et al., 2023). For example, the production of active pharmaceutical ingredients and antibiotics often involves high levels of environmental pollution. Additionally, the release of these substances into the environment due to improper disposal of medications by consumers can promote the development of antibiotic resistance, a problem that threatens global public health, with projections indicating possible millions of deaths annually due to antibiotic-resistant infections. Flushing medications down toilet or sink causes groundwater pollution, and disposal in the trash could also harm animals' health, as they are easily attracted to the smell of certain substances (Kinrys et al., 2018). Besides, health issues can arise also due to the bad storage at home, as well as keeping them easily accessible to children (Chung and Brooks, 2019). Considering return management, take-back programs are organized to allow consumers returning unused or expired medications to collection points usually located near pharmacies, hospitals, and local government agencies (e.g., Misericordias in Italy) (Ingale et al., 2023). However, many people are unaware of proper disposal options for medications or prefer to keep them at home, often ending up disposing of them in general waste when they expire. This leads to significant environmental impacts due to the release of harmful substances, and a waste of still-valid medications that could benefit those who cannot afford them. Inefficient and inadequate drug disposal represents a significant source of pollution and resource waste, affecting both environmental and human health. Making more informed decisions can significantly reduce these impacts, while ensuring fair access to valid medications for those in need. Addressing this issue is crucial to mitigate negative externalities and promote responsible medication management, requiring a deeper investigation of consumer attitudes and external factors influencing their behaviors. Simulation is a versatile methodology that can be used in the field of the circular economy to model and analyze complex systems (Wu et al., 2024), allowing the exploration of different scenarios and the prediction of the effects of decisions on resource consumption and waste (Mashhadi et al., 2016; Tong et al., 2018). Even if different simulation techniques have been used by researchers, the most discussed in recent years has been the Agent-Based Modelling (ABM), especially for the simulation of behaviors of multiple agents. These agents can represent individuals, groups, organizations, or other entities that act and interact based on specific behavioral rules. In this way, social interactions between agents can also be analyzed, providing insight into how individual decisions influence and are influenced by the decisions of others. This is useful for understanding behaviors such as word-of-mouth, which plays a significant role in the spread of sustainable practices among consumers (Koide et al., 2023).

Despite the pharmaceutical sector has a significant impact on the environment and society and peculiarities, making the analysis and implementation of circular economy practices crucial to mitigate these impacts, no studies that used simulation applied to this specific sector can be found, at the best of authors' knowledge. Accordingly, the present work proposes a simulation model to evaluate different strategies for promoting an effective return management of expired medications as well as the still-valid-but-not-used ones, considering the crucial role of consumers to close the loop. More specifically, ABM simulation is used to model consumer behavior, analyze their choices regarding the return of medications, and evaluate different solutions to increase the number of well-disposed items, thus improving collection and disposal strategies and reducing environmental and social impacts. A practical application with real data is provided, to outline empirical insights for decision-makers considering customers' behavior and localization of collection points of a specific geographical area.

The paper is structured as follows: Section 2 provides the theoretical background of the research; in Section 3, the proposed simulation model is described, and main results are shown and discussed in Section 4; finally, Section 5 resumes the main conclusions, limitations, and future developments for the proposed work.

2. Theoretical background

2.1. Consumers' behavior in circular economy

Several contributions can be found in literature, highlighting different aspects to consider when investigating consumers' behavior for returning products at their end-of-life, as well as initiatives to carry out to promote take-back programs. As expected, environmental aspects are the mostly investigates, including consumers' environmental sensitivity (Farida et al., 2023), often analyzed together with social concerns (Ratay and Mohnen, 2022). Some authors refer to the level of knowledge and accessibility of product collection centers as one of the major factors positively influencing consumer decisions regarding product returns, as scarce awareness of that information, even in case of high awareness of environmental and social concerns, compromise the effectiveness of take-back programs (Shi et al., 2023; Ylä-Mella et al., 2015). Besides, regulatory aspects, such as public campaigns (Shi et al., 2023) to encourage proper consumer behavior, are not widely considered mainly due to the lack of penalties when the appropriate behaviors are not adopted (Farida et al., 2023). According to the main aspects influencing consumers' behavior in returning products at their end-of-life, several initiatives are presented in the literature. One of the most discussed action to implement to increase consumers' awareness is educating them, considering for example social media, which are the main source of information (Farida et al., 2023). The effects of environmental appeals of a returning program strictly depend on consumer environmental awareness (Ratay and Mohnen, 2022), making public campaigns encouraging the return of products often effective even in the absence of benefits offered (Botelho et al., 2016). From companies' perspective, (Ding et al., 2023) highlights the importance of mission statement and communication in making consumers aware of the company's efforts towards sustainable behavior and thus influencing their choices. Some industry, according to the residual value of returned products, can leverage on economic incentives to promote take-back programs. Regarding the type of reward, studies considering cell phones highlight that intentions to use return options with cash rewards are higher than intentions to use options offering a combination of cash and donation or those offering only a donation. However, in the case of higher environmental awareness, the consumer may prefer options that do not involve monetary rewards, such as donation rewards (Ratay and Mohnen, 2022). As far as reported in the extant literature, and also confirmed by Das and Dutta (2022), consumers return used products to companies mainly through three methods: receiving vouchers, purchasing the new product at a reduced price, and selling the used product directly to companies without being tied to the purchase of a new product. Finally, to reduce barriers related to the accessibility of product collection centers, some authors propose to increase the number of such points and make them closer to consumers (Ylä-Mella et al., 2015).

2.2. Returning process in the pharmaceutical industry

Due to the relevance of unproper drugs disposal, several contributions investigate the behavior of consumers for expired and unused medications, especially through questionnaires to grasp empirical evidence. The options for pharmaceutical waste disposal included in these analyses are: keep at home, dispose in trash, flush down sink / toilet, and take-back to dedicated collection points (e.g., drop-off at pharmacies, hospitals, or local government agencies). To better depict specific scenarios and influences, authors mostly focus on specific countries, with main contributions for USA regions (Athern et al., 2016; Ehrhart et al., 2020; Law et al., 2015; Petrik et al., 2019; Thach et al., 2013; Tai et al., 201), followed by studies in China (Chung and Brooks, 2019; Lv et al., 2021), India (Raja et al., 2022), and Serbia (Paut Kusturica et al., 2020). For instance, studies conducted in USA refers to the central role of many American agencies, including the Food and Drug Administration, the Environmental Protection Agency, and the Drug Enforcement Agency, to provide clear guidance and recommendations on the management of unused medications through medicine take-back programs or authorized collection sites (Athern et al., 2016; Petrik et al., 2019). Considering the Chinese scenario, the evidence from (Chung and Brooks, 2019) show that, despite environmental awareness campaigns promoted in recent years by the Chinese government having positive effects on citizens to recycling in general, there is a lack of specific attention in educating the population regarding the use, storage, and disposal of medications.

Despite the environmental and social risks associated to a wrong disposal of medications, the literature highlight that most consumers disposes them in trash, flushes drugs down sink / toilet, or at least keeps them at home, even if unused, until the expiration date. With a huge consensus, take-back programs are not widely utilized. Most of the contributions focuses on consumers' awareness of environmental and social issues and their knowledge about proper product disposal at its end-of-life. The importance of properly educating individuals on take-back programs and local regulations to reduce the number of medications wrongly disposed by consumers is highlighted by several authors (Athern et al., 2016; Ingale et al., 2023; Kinrys et al., 2018), as well as a scarce level of knowledge of awareness of both the existence and location of collection points (Banjar et al., 2022; Ehrhart et al., 2020; Lv et al., 2021). While a wide consensus can be found about a general lack of knowledge on the appropriate disposal methods for medications, different evidences are collected considering the individuals' awareness of environmental and social risks associated with improper medication disposal. On the one hand, some contributions highlight that consumers, despite being unaware of the alternative options, are aware of the environmental risks associated with improper medication disposal (Athern et al., 2016; Raja et al., 2022; Paut Kusturica et al., 2020). On the other hand, other studies show a poor knowledge of the risks associated with improper disposal (Banjar et al., 2022; Chung and Brooks, 2019; Ehrhart et al., 2020; Lv et al., 2021; Paut Kusturica et al., 2020). Other reasons that negatively influences consumer choices in returning medications to collection points are low level of education (Paut Kusturica et al., 2020) and long distance from the collection centers (Lv et al., 2021), the latter particularly relevant in the case of medications, which are often used by elderly individuals who may not be able to drive to the return location (Thach et al., 2013). Besides, (Lv et al., 2021) highlight that if the intention to make the right choice is very strong (i.e., environmental and social attitude), the consumer is more inclined to accept the additional efforts and will decide to take the medications to the collection points.

The central role of pharmacists has been highlighted by several authors. Pharmacists are expected to be the ones knowledgeable about the appropriate use of medications and correct behavior regarding medication disposal, as well as the location of medication collection centers in the pharmacy's area, as well as the proper waste disposal procedures (Law et al., 2015). Many patients, especially those who regularly take numerous medications, have a trusting relationship with the pharmacists at their reference pharmacy and may turn to them for advice on the proper disposal of medications (Athern et al., 2016). The importance of communication to increase consumer awareness is also emphasized by (Petrik et al., 2019), who highlight that misleading information can be provided also by media services, not always reporting the correct recommendations and, therefore, negatively influencing consumer behaviors. (Tai et al., 2016) also declare that communication regarding medication disposal between pharmacists and customers varies widely and often depends on the individual pharmacist. Investments in awareness campaigns should therefore also involve pharmacists, given their fundamental importance in customer education.

Despite these contributions demonstrate the critical issues related to returning process in the pharmaceutical industry that strictly depend on country-specific factors, to the authors' knowledge, only explorative studies can be found in the literature.

2.3. ABM and Circular Economy

Simulation offers a powerful method for exploring the effects of different strategies and scenarios that aim to close the loop, enabling scholars and policymakers to test hypotheses, evaluate alternatives, and predict potential outcomes. To investigate the effect of interactions among different stakeholders or specific policies on system’s performance (e.g., recovery rate), ABM is used considering behaviors and interactions among autonomous and rational agents. Waste recycling and disposal behaviors of households have been investigated through simulation, as well as rental services, but considering electronic products such as appliances (Koide et al., 2023; Luo et al., 2019) and cell phones (Mashhadi et al., 2016; Raihanian Mashhadi et al., 2019). Tong et al. (2018) carry out a social experiment in China to understand if social norms had a positive effect on households' choices to recycle waste. In their study, several factors influencing households attitude have been considered, in particular: socioeconomic status (i.e., education level and income), cognitive status (i.e., awareness of environmental issues and knowledge about the importance of recycling), local status (i.e., social networks, number of neighbors and friends), and behavior constraints (i.e., time available for recycling activities, distance to recycling bins, and space available for recycling). The scenario analyses conducted through ABM show that knowledge of recycling and distance to recycling facilities are the most influential factors on the recovery rate, confirming raising awareness through public media and planning physical recycling facilities at the municipal level as effective initiative to implement. To this evidences, the study of (Luo et al., 2019) focused on appliances shows that a greater awareness of environmental issues leads consumers towards more sustainable choices. The study further demonstrates through scenario analysis that the recovery rate of appliances can increase through specific policies, such as increased government training programs or the introduction of a compensation/penalty system based on citizens' behavior. Considering cell phones disposal at the end-of-life, (Mashhadi et al., 2016) compare through ABM different options for consumers: selling the product, throwing it away, returning it to the manufacturer, or keeping it at home even if they no longer use it. Again, multiple attributes are considered: sociodemographic characteristics (i.e., education level and income), social pressure (i.e., impact of choices made by other consumers within the network, assuming that each consumer is connected in the network with other 1 to 10 consumers), knowledge of recycling programs, product-related attributes (i.e., price of used items and type of sensitive data contained in the product), and accessibility to collection centers. The article then analyzed the impact of interactions in two scenarios, one where all consumers have the same concern about environmental issues and one where consumers are divided into three groups based on the level of concern. The choice between renting a product or purchasing a new one is addressed by (Koide et al., 2023), who investigate how the decision-making process is influenced by information from the outside. Through active research or through the influences of a network, such as word of mouth or advertising, the consumer becomes aware of the offers and chooses whether to rely on a service or to purchase the product. In this study, simulation was used to evaluate how the percentage of customers choosing to join a service for renting refurbished appliances varies in relation to the different promotions offered. Several scenarios were considered, starting from one without promotions up to scenarios with increasingly advantageous promotions, such as service price reductions. Similarly, (Raihanian Mashhadi et al., 2019) demonstrate that service price play a significant role in consumers choice between renting and buying, as well as social influence.

Despite these contributions demonstrate the effectiveness of using ABM to evaluate factors and initiatives that significantly influence disposal choices, to the authors' knowledge, no similar studies have applied it to the pharmaceutical sector.

3. Simulation Model

To overcome literature gap, a simulation model is developed to include a series of agents interacting each other during the process of purchasing, using, and disposing of medications. Accordingly, this section provides information about the agents included in the model, the scenarios analyzed and the data collection process to grasp empirical evidence. The simulation aims to compare different action plans applicable to various agents to increase the number of medicines properly disposed. Depending on the consumers' awareness and attitudes on social and environmental aspects, they can choose between proper or improper disposal of valid but unused or expired medications. As accessibility to collection points is one of the main drivers to good disposal, the agent-based simulation is integrated with GIS tools to calculate the distance between consumers' residences and collection centers. Starting from literature evidence, the table below indicate the main factors that influence consumers in returning expired or still valid medications to a collection point (Table 1).

Table 1: Parameters per agent

Symbol	Parameter	Agent
$AQDP_C$	Average Quantity of Drugs Purchased in Pharmacy	Consumer
$AECP_C$	Awareness of Expired Medication Collection Points	Consumer
$AMCP_C$	Awareness of Misericordia Collection Points	Consumer
EA_C	Environmental Attitude	Consumer
SA_C	Social Attitude	Consumer
FCE_C	Frequency of Checking Expired Medications	Consumer
FPV_C	Frequency of Pharmacy Visits	Consumer
KER_C	Knowledge of Environmental Risks	Consumer
KSB_C	Knowledge of Social Benefits	Consumer
MD_C	Maximum Distance for Drug Delivery	Consumer
WCO_C	Willingness to Change Opinion Based on Social Influence	Consumer
WDM_C	Willingness to Discontinue Valid Medication	Consumer
$WSUM_C$	Willingness to Stop Using Medication	Consumer
WSI_C	Willingness to Share Information with Connections	Consumer
WUM_C	Willingness to Use Medication Until Completion	Consumer
$AECP_P$	Awareness of Expired Medication Collection Points	Pharmacist
$AMCP_P$	Awareness of Misericordia Collection Points	Pharmacist
WSI_P	Willingness for Sharing Information	Pharmacist
D_M	Distance to Misericordia	GIS Map
D_P	Distance to Pharmacy	GIS Map

$D_{P\text{-}M}$	Distance from Pharmacy to Misericordia	GIS Map
$D_{M\text{-}P}$	Distance from Misericordia to Pharmacy	GIS Map

3.1. Agents

This section shows the roles and parameters for the different agents within the simulation model. The agents under consideration include (i) Pharmacies, (ii) Misericordia Collection Points, (iii) Medications, and (iv) Consumers.

3.1.1. Pharmacies

Pharmacies are places where medications can be purchased and where consumers can properly dispose of expired medications. The pharmacy parameters are $AECP_P$, which determines if the pharmacist knows the location of expired medication collection points; $AMCP_P$, which checks if they know the location of valid medication collection points; and WSI_P, which is the probability of the pharmacist sharing this information without the customer asking. It is determined here that the initiative to start the conversation about medication disposal will not come from the pharmacist.

3.1.2. Misericordias

Misericordias are Italian organizations dedicated to providing medical and social assistance. These centers are responsible for collecting valid medications disposed by consumers. These medications can be repurposed for people in vulnerable situations who cannot afford to purchase them. As they are just collection points, the Misericordias cannot change the agent behavior, nevertheless, a long distance from consumer residence can be a barrier for a good disposal. Therefore, the only role of these agents in the simulation is to collect the medications.

3.1.3. Medications

Medications are agents that interact directly with all other agents but do not have the power to change any behavior. They can only be acquired at Pharmacies and may expire if not consumed by the expiration date (with a probability $WSUM_C$), may be discontinued while still valid (with a probability of WDM_C), or may be fully consumed by consumers (with a probability $WUM_C = (1 - WDM_C) * (1 - WSUM_C)$).

Table 2 shows how the relationship between variables can impact the proper or improper disposal of medications. Expired medications can have two endings: wrong disposal (garbage) or right disposal (pharmacy). On the other hand, valid but unused medications can have three fates: wrong disposal (garbage), wrong disposal (pharmacy), and right disposal (misericordia). For valid medications, although disposal at a pharmacy is environmentally correct, it could have a more significant social role by being reused by those in need. Therefore, while pharmacy disposal is correct, it is considered socially inadequate.

Table 2: Variables correlation influencing proper disposal of expired medications

EA_C	KER_C	$AECP_C$	SA_C	KSB_C	$AMCP_C$	D_M	**Result**
○	–	–	–	○	–	–	Wrong Disposal (Garbage)
○	–	–	○	–	–	–	Wrong Disposal (Garbage)
–	○	–	–	○	–	–	Wrong Disposal (Garbage)
–	○	–	○	–	–	–	Wrong Disposal (Garbage)
●	●	●	–	○	–	–	Wrong Disposal (Pharmacy)
●	●	●	○	–	–	–	Wrong Disposal (Pharmacy)
●	●	○	–	○	–	–	Seek information
●	●	○	○	–	–	–	Seek information
–	–	–	●	●	○	–	Seek information
–	–	–	●	●	●	○	Keep medicine
–	–	–	●	●	●	●	Right Disposal

●Positive ○ Negative – Indifferent

3.1.4. Customers

Consumers are the main agents in the simulation. They are responsible for buying, using, and disposing of medications. Initially, all agents are at their residences. There are two processes that agents can follow: checking medications and visiting pharmacies. The process of checking medications is started regularly, according to rate FCE_C, and cannot be started in any other way. The process of visiting the pharmacy is also started regularly, according to rate FPV_C, but it can also be started internally during the medication checking process.

During the process for Checking Medication, if the consumer is not aware of the social benefits (KSB_C) and does not have a social attitude (SA_C), they will add the medications to the expired group. Otherwise, they will separate these medications for proper disposal (Q_{Val}). Next, if they are not aware of the environmental risks (KER_C) not have an environmental attitude (EA_C), they will improperly dispose (in garbage) the expired medications. Otherwise, they will separate these medications for proper disposal (Q_{Exp}).

After checking, if there are expired medications and the distance to the pharmacy (D_P) is reasonable, the consumer will go to the pharmacy and start the Pharma Visit process. If there are no medications or the distance is greater than the customer is willing to travel (MD_C), they can still make decisions regarding valid medications, if any. If there are no valid medications, nothing happens. If they do not know where to properly dispose of valid medications ($AMCP_C$) and D_P is greater than MD_C, the customer will stay home. Otherwise, if

$AMCP_C$ is still negative but the distance is acceptable, they will go to the pharmacy and start the Pharmacy Visit process.

On the other hand, if $AMCP_C$ is positive and the distance to Misericordia (D_M) is not acceptable, nothing will happen. But if the distance is acceptable, the costumer should move to Misericordia and properly dispose the valid medication. Still at Misericordia, it can check if there are expired medications and if D_P is now acceptable. If so, it should move to the nearest pharmacy and start the Visit process. Otherwise, it should return home. This process is presented in Figure 1.

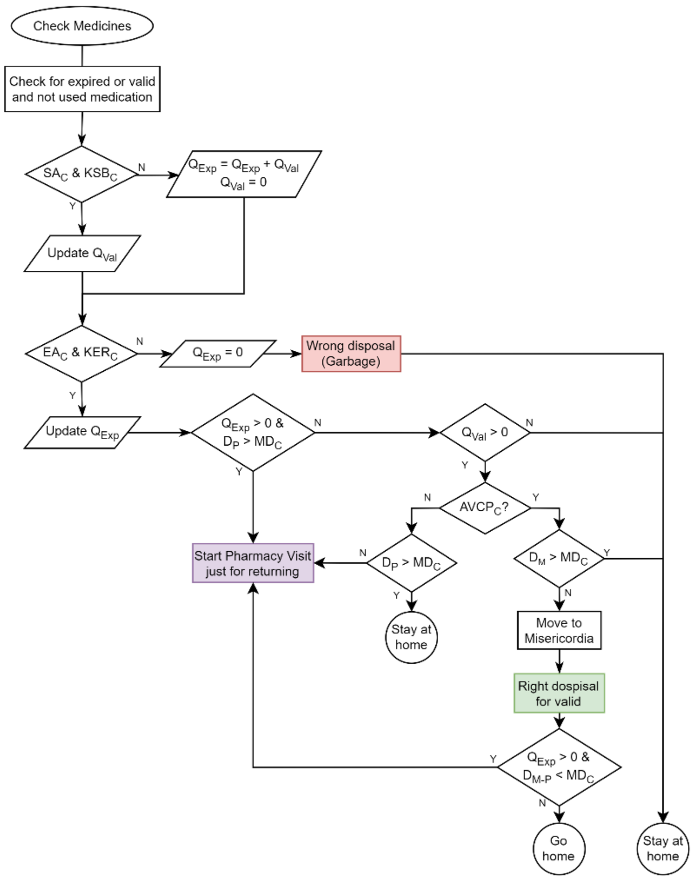

Figure 1: Checking medicines process flow

The Pharmacy Visit process is showed in Figure 2 and can start either due to the regular frequency the consumer goes to the pharmacy FPV_C, indicating that a medication purchase will be made (according to the average of bought medications by agent - $AQDP_C$), or through the medication checking process, indicating that the visit will be for returns only.

The process begins with the client going to the pharmacy. If the customer has no medications to return, it buys new medications. However, if it has medications to return, the interaction between the customer and the pharmacist begins. During this interaction, they can acquire information about disposal locations.

If, after the interaction, the customer knows how to dispose of medications (*$AECP_C$*) and has any expired medications, it will dispose of them correctly. If they have valid medications that it previously considered expired (due to lack of knowledge about social benefits or social attitude), it will incorrectly dispose the medications. However, if it still does not know the disposal location for expired medications or have no medications to return, it may still purchase medications if the visit is not solely for returns.

After buying and disposing medications, if the costumer still has valid medications to dispose, the distance is acceptable, and if it knows the disposal location, it will go to the closest Misericordia, make the proper disposal, and return home. Otherwise, they will go directly home.

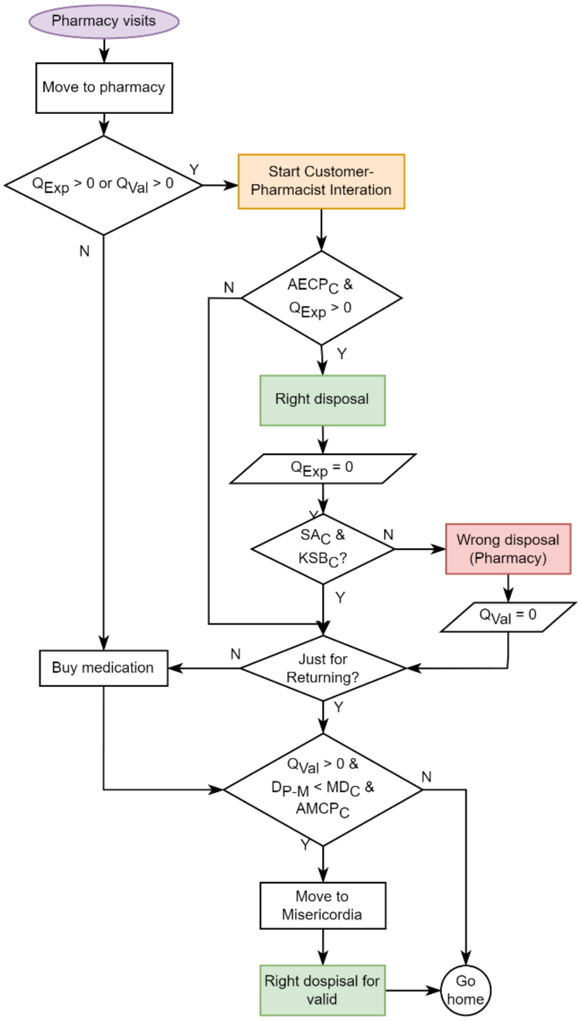

Figure 2: Visiting pharmacies process flow

Finally, the Customer-Pharmacist interaction can be started only during the pharmacy visit and always by the customer, not the pharmacist. During the interaction, if the customer has expired medications to return, doesn’t know the disposal location, and the pharmacist can provide this information, the customer acquires knowledge of the disposal location for expired medications.

Next, if the customer has valid medications, does not know the disposal location, and the pharmacist knows where to dispose of valid medications, the customer acquires this knowledge as well. Otherwise, it is still possible for the pharmacist, on its' own initiative (if it knows), to share the information about the collection point for valid medications with the customer. The process is showed in Figure 3.

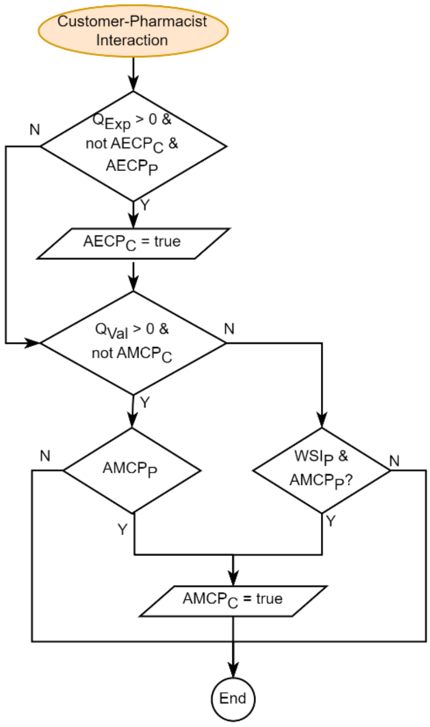

Figure 3: Customer-Pharmacist interaction process flow

3.2. Scenarios

Four different scenarios will be compared, analyzing how changes in each agent can influence the system. Table 3 presents the relationship between each possible action and the achieved result. All actions will be explained in depth in the following subsections.

Table 3: Scenario analyses

Scenario	Description	KER_C	KSB_C	EA_C	SA_C	$AECP_C$	$AMCP_C$	$AECP_P$	$AMCP_P$	D_M
S1	Baseline	●	●	●	●	●	●			
S2	Advertising	●	●			●	●			
S3	Pharmacist Training							●	●	
S4	More Collection Points									●

●Impact

The baseline scenario (S1) is considered the standard system and will be kept in parallel with other actions. In this scenario, consumers interact with each other and may share information and influence each other. According to several contributions, indeed, word of mouth and generally social networks represent one of the main leverages for changing customers' own perception (Mashhadi et al., 2016; Tong et al., 2018). The interaction occurs when medications are delivered at the pharmacy and at Misericordia collection points. Upon disposal, there is a probability WSI_c that the customer will send a message to their close contacts about the event. When this contact is made, it is assumed that the connected customer will acquire the same knowledge as the customer. Additionally, there is a probability WCO_C that the customer will influence their connections, leading them to develop a positive environmental and/or social attitude. Advertising (S2) explores how potential marketing actions to disseminate relevant information. Educating customers to proper disposal practices is the most common initiative investigated in the existing literature (Athern et al., 2016; Farida et al., 2023; Ingale et al., 2023; Kinrys et al., 2018; Luo et al., 2019; Ratay and Mohnen, 2022; Tong et al., 2018). In this case, the information can be transmitted through tools such as television, radio, and social media. As a result, population will acquire knowledge about environmental risks (KER_C), social benefits (KSB_C), and the correct locations for medication disposal ($AECP_C$ and $AMCP_C$). The Pharmacist Training action (S3) aims to explore how educational initiatives in pharmacies impact the general knowledge of the population. Avoiding misleading information from pharmacists is therefore one of the initiatives to implement, according to trust-based relationships that can occur between customers and them (Tai et al., 2016). This action enhances pharmacists' awareness of collection points for expired ($AECP_P$) and valid ($AMCP_C$) medications and increases the likelihood that pharmacists will spontaneously provide this information (WSI_P). Finally, the last action More Collection Points (S4) aims to analyze the effects of additional collection points beyond Misericordia. The distance from home to collection centers represents the main barrier investigated in the literature that is not influenced by personal awareness about the topic, making the addition of new collection points one of the strategy to reach conscious customers (Ylä-Mella et al., 2015; Tong et al., 2018). These new points are intended to reduce the distance between residences and collection locations (D_M), thereby facilitating medication disposal. In this scenario, hospitals and health units will be included.

3.3. Data Collection

To provide practical evidence, the proposed model is applied in the city of Florence, Italy. According to other contributions, a specific geographical area outlines population peculiarities and better suggests effective initiatives according to initial population characteristics, as the work of Ehrhart et al. (2020) within the city of Portland. Figure 4 presents the simulated model, where the red buildings represent 24 Misericordia collection centers (i.e., responsible for collecting valid medications), the green buildings represent 108 pharmacies (i.e., responsible for collecting expired medication), and the blue buildings represent residences. The locations of the pharmacies and collection centers are real and were obtained via Google Maps, while location for residences is randomly defined.

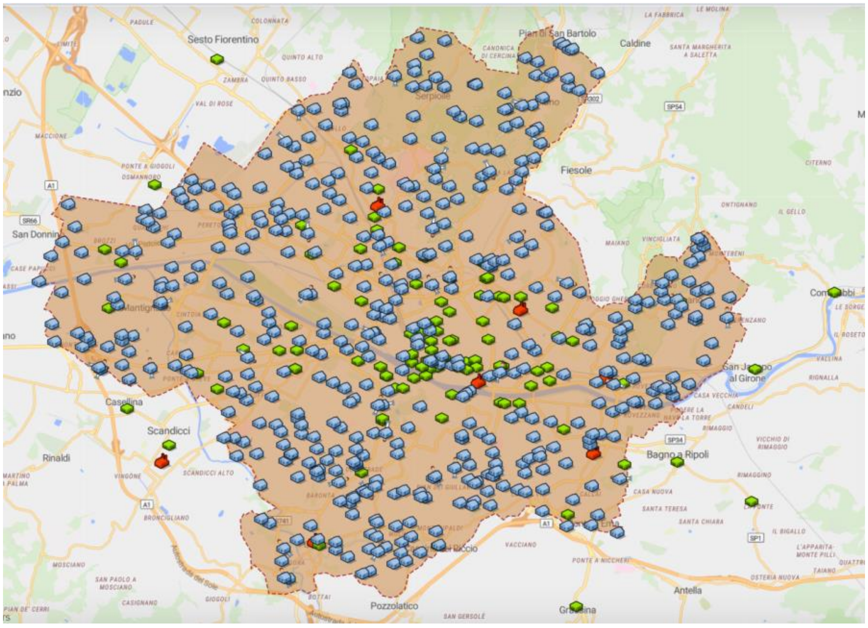

Figure 4: Simulation model

In line with the approach of Tai et al. (2016), we investigate consumers' and pharmacists' behavior through a questionnaire administered to consumers and interviews conducted with pharmacists located in the addressed area, reaching 278 consumers and 26 pharmacists respectively. The questions were specifically designed to fill up the parameters defined in Table 1. The survey results were analyzed, and two clusters of population profiles were determined using the K-means algorithm, as presented in Figure 5.

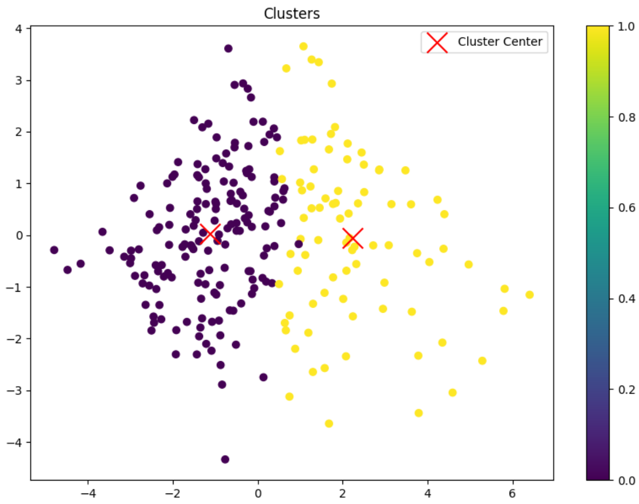

Figure 5: Customer clusters

The previously presented profiles are referred to here as “Group 1” and “Group 2”. Group 1 constitutes 66,4% of the population and is characterized as most aware of the risks and proper disposal locations for both valid and expired medications. This group also exhibits a more positive attitude towards environmental and social issues. However, Group 2 shows a greater willingness to change their opinion on these issues (positively), purchases a smaller quantity of medications, and visits the pharmacy less frequently. The statistical analysis for each group is present in Table 4. Normal distributions are presented in AnyLogic® format *normal(std, mean)*.

Table 4: Parameters per cluster of consumers

Parameter	Total	Group 1	Group 2
Population	100.0%	66.4%	33.6%
KER_C	38.87%	48.78%	19.28%
KSB_C	66.4%	78.05%	43.37%
$AECP_C$	88.66%	98.17%	69.88%
$AMCP_C$	39.27%	46.95%	24.1%
EA_C	76.52%	90.85%	48.19%
SA_C	55.87%	59.15%	49.4%
FPV_C	normal(0.2072, 0.6046)	normal(0.1585, 0.6555)	normal(0.2508, 0.504)
FCE_C	normal(0.2511, 0.3700)	normal(0.2211, 0.4402)	normal(0.2493, 0.2313)
WUM_C	normal(0.2359, 0.5324)	normal(0.2130, 0.5701)	normal(0.2598, 0.4578)
WDM_C	normal(0.1702, 0.3684)	normal(0.1419, 0.3329)	normal(0.1975, 0.4386)
WCO_C	normal(0.1814, 0.5810)	normal(0.1736, 0.5701)	normal(0.1942, 0.6024)
WSI_C	normal(0.2118, 0.6356)	normal(0.1969, 0.6845)	normal(0.2071, 0.5392)
MD_C	normal(0.2716, 0.6012)	normal(0.2648, 0.6448)	normal(0.2642, 0.5151)

Besides, Table 5 presents the probabilities of each of the discussed parameters for pharmacies.

Table 5: Parameters for pharmacies

Parameter	Probability
$AECP_P$	80.77%
$AMCP_P$	84.62%
WSI_P	65.38%

4. Results and discussion

The results will be explored from three perspectives: (i) impacts on environmental parameters, (ii) impacts on social parameters, and (iii) impacts on disposals. The environmental parameters include the percentage of the population that knows about environmental risks, is aware of collection points, and has an environmentally conscious attitude. The social parameters include the percentage of the population that knows about social benefits, is aware of collection points for valid medication, and has a socially conscious attitude. Finally, the impact on disposals includes the percentage of the population disposing of medications in the garbage, expired medications in pharmacies, valid medications in pharmacies, and valid medications in Misericordias.

4.1. Environmental parameters

Figure 6 presents the share of the population that is aware of the environmental risks associated with the improper disposal of medications. Initially, S2 shows the highest performance, exceeding the other scenarios by 4.81%. However, all strategies demonstrate comparable improvements and similar growth rates over time. In the long term, advertising keeps a slight advantage, with a reduced lead of 0.72% over the other scenarios. These results suggest that all strategies yield similar performance.

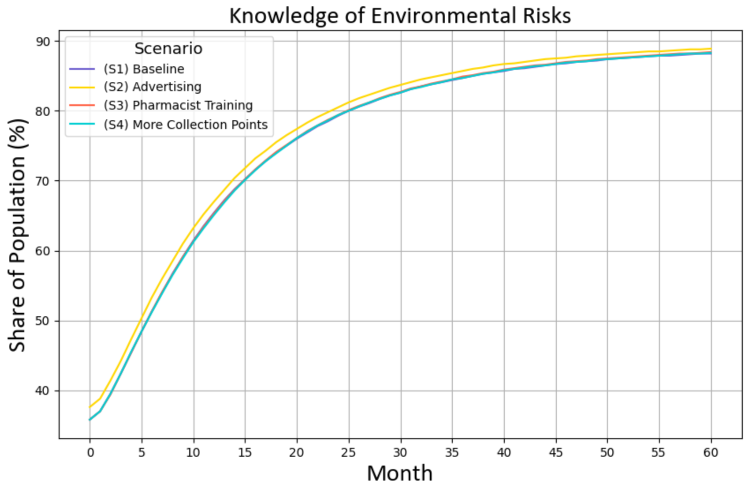

Figure 6: Knowledge of environmental risks for unproper disposal of expired medications

Considering the awareness of collection points for expired medication, as presented in Figure 7, S2 outperforms the others. In contrast, S1, S3 and S4 exhibit similar performance levels. Over time, awareness converges across all strategies, indicating that the initial advantage of S2 decreases, resulting in comparable long-term outcomes for all strategies. This suggests that while advertising may offer an immediate advantage, the other strategies achieve similar results in the long term.

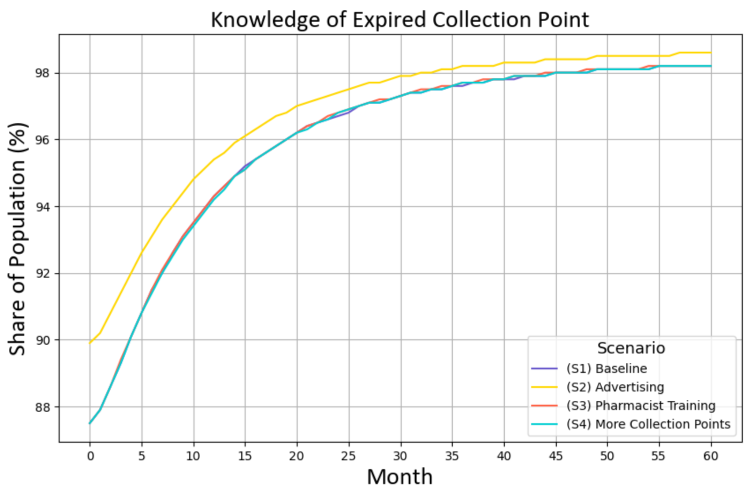

Figure 7: Knowledge of collection points for expired medications

Figure 8 shows the overall evolution of the population's environmental attitude. It can be noted that all strategies converge closely, making the differences in performance negligible.

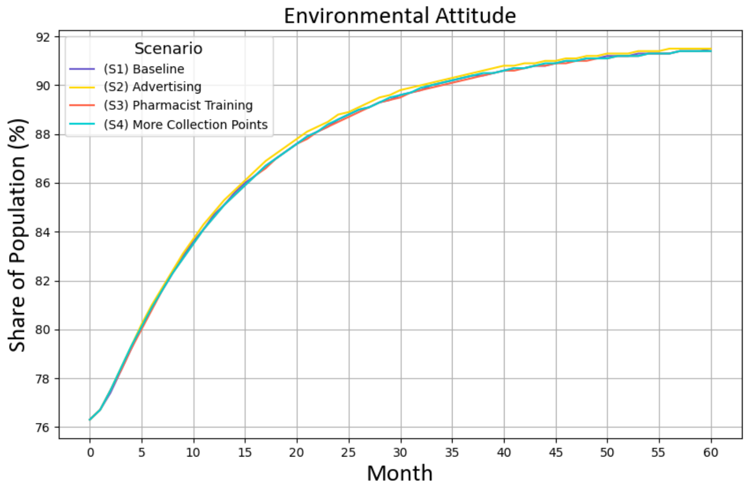

Figure 8: Environmental attitude

All three environmental KPIs indicate that the ecological perspective of the studied population is not significantly impacted by any scenario. Even for the awareness of collection points for expired medications, which shows a slight improvement with the advertising strategy, the performance difference in the long term is only 0.4%. These results can be better understood by considering the profiles within the system. On average, 88.6% of the population already knows about the collection points for expired medication, and 76.5% has an environmental attitude. In fact, although Italian consumers' behavior has never been investigated in the literature, results from surveys show a general higher knowledge of take-back programs than results from literature (Banjar et al., 2022; Ehrhart et al., 2020; Lv et al., 2021). On the one hand, even know about the correct place to dispose of medications, the population of Florence align with literature as only 38% of the population knows about the risks related to improper disposal (Banjar et al., 2022; Chung and Brooks, 2019; Ehrhart et al., 2020; Lv et al., 2021; Paut Kusturica et al., 2020).

In this perspective, the combination of awareness of collection points and environmental attitude decreases the initial impact of any new actions, as the population is already well-informed. The increasing trend in all parameters is likely to occur naturally in each scenario because society already has a high level of concern about this topic, and individuals are free to share information with their connections. Therefore, pharmacist training does not significantly impact environmental issues in this context. Additionally, adding more collection points for valid medications does not affect the disposal of expired medications, as these cannot be disposed of in Misericordias, meaning the distance to pharmacies remains unchanged. The advertising strategy shows some advantage when used. However, since all scenarios eventually converge and achieve similar results, it can be concluded that social networks between individuals are the main factor in improving social consciousness about environmental issues. Connections with close friends, which can also be understood as social pressure, may influence individual attitudes, creating a snowball effect throughout society without relying on external interventions.

4.2. Social parameters

Figure 9 presents the evolution of the population's awareness of social benefits. The results show that the S2 starts with the highest performance and maintains a leading position in the early months. However, it is eventually surpassed by S4, which achieves the best results, outperforming all other strategies. S3 and S1 demonstrate slower growth in comparison.

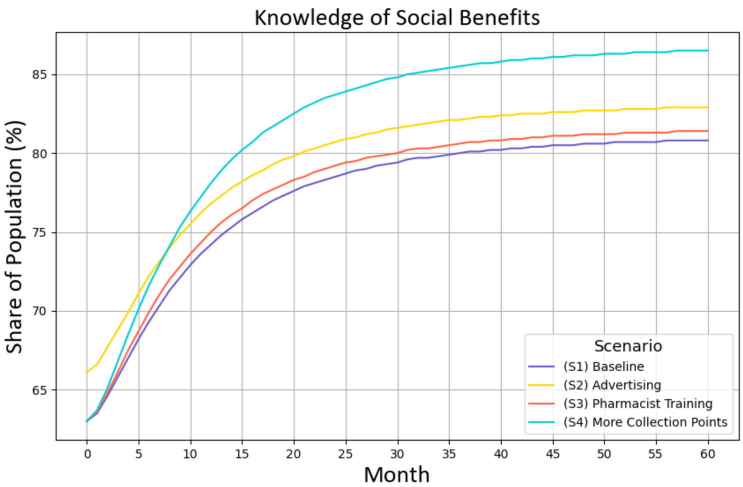

Figure 9: Knowledge of social benefits for proper disposal of valid medications

Regarding the awareness of collection points for valid medication, S2 initially shows the highest performance, as presented in Figure 10. However, S3 and S4 show faster improvement rates. Notably, S4 eventually surpasses all others, indicating its superior long-term effectiveness. These results suggest that while advertising is effective for short-term gains, providing training and adding new collection points offer superior long-term benefits.

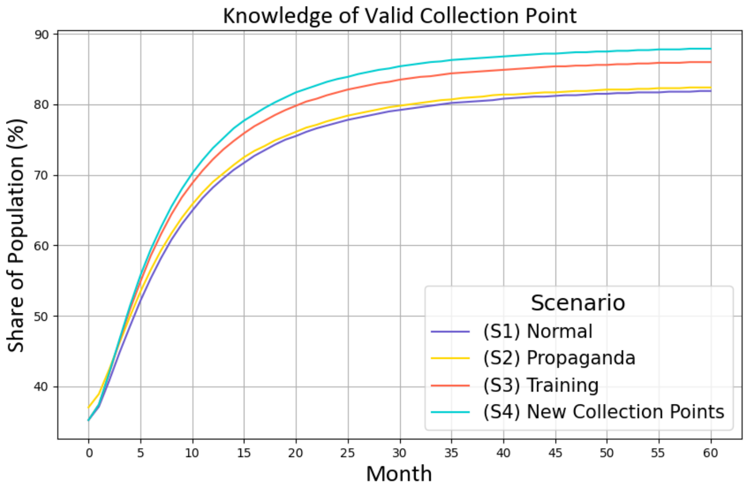

Figure 10: Knowledge of collection points for valid medications

Figure 11 shows the overall evolution of the population's social attitude. Initially, all strategies are at the same level. However, S4 consistently shows the highest increase over time. This contrasts with the S2, which lags slightly behind the others. Both S3 and S1 follow similar trajectories, indicating slower growth. Overall, the analysis highlights that S4 is the most effective in the long term, achieving the highest performance.

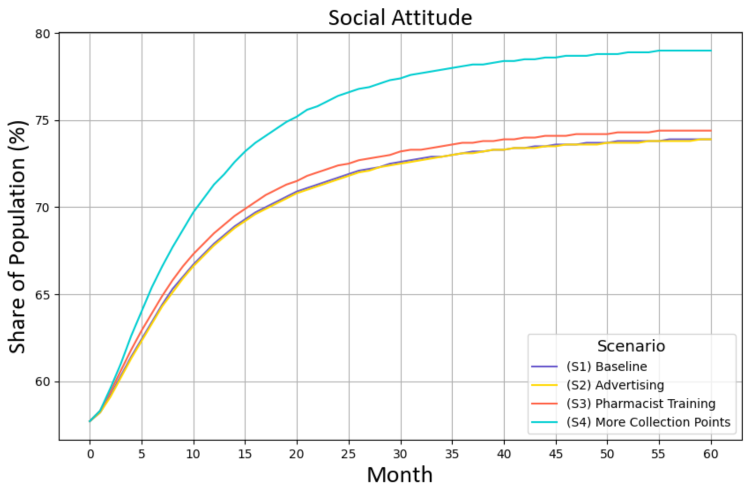

Figure 11: Social attitude

The results for social parameters align with those found for environmental parameters. On average, the social parameters show lower values, with 39.3% of the population knowing the correct disposal location for valid medications and 55.87% with social attitudes. However, 66.4% of the population is aware of the social benefits, a much higher result than those who know about the environmental risks. This difference in parameters suggests that social parameters have more opportunities for evolution and improvement.

Indeed, all results indicate that various actions, particularly pharmacist training and the addition of new collection points, show superior outcomes compared to S1. Pharmacist well-trained can inform more people about collection points, increasing the number of people returning valid medications. Additionally, more collection points encourage more people to dispose of medications correctly, as the distance to the disposal site is reduced with the addition of more points. These results highlight an important factor regarding connections between individuals. The more people correctly disposing of medications and sharing information, the more others are influenced by these positive behaviors. Therefore, actions should focus on increasing the exchange of information among individuals. These actions promote information exchange, making individuals responsible for the overall improvement of society.

4.3. Disposal practices

Figure 12 shows the share of population disposing of medications in garbage and reveals a decreasing trend across four different strategies. Initially, all strategies start from a high baseline, but all scenarios present a steady decline over time. This consistent downward trajectory indicates that all four scenarios are effective in reducing incorrect disposal. The sharpest decline is observed in S4 strategy, which starts at the worse result but has a more significant decrease compared to the others. In contrast, while S1, S2, and S3 begin at similar levels, they ultimately converge towards similarly low final values.

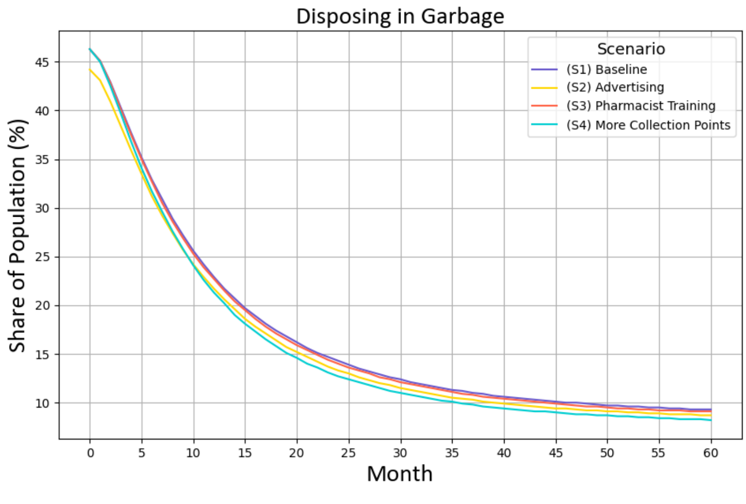

Figure 12: Unproper disposal of expired and valid medications in garbage

The share of population that correctly dispose of expired medication is presented in Figure 13. Advertising shows a slightly better result compared to the other scenarios throughout all the timeline, even if all strategies exhibit significant growth. This consistent upward trend indicates the effectiveness of all four strategies in improving the correct disposal.

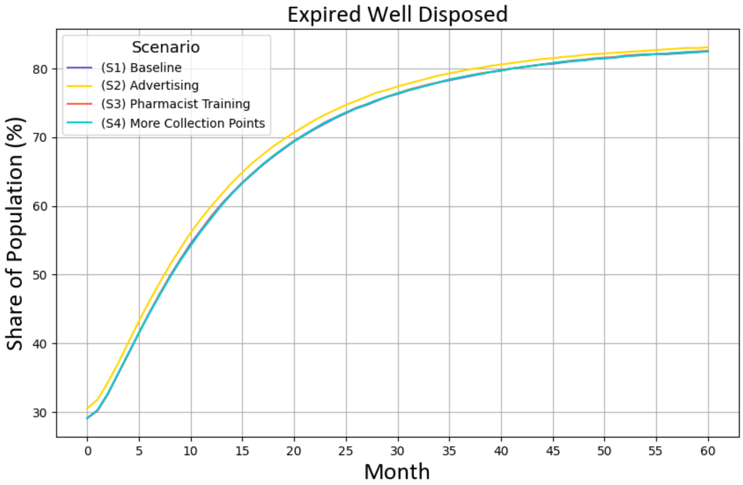

Figure 13: Proper disposal of expired medications

Figure 14 shows the share of the population correctly disposing of valid medication. Although each strategy demonstrates a consistent upward trend, S4 strategy starts with results 43.39% better than the alternatives. This initial advantage translates into a continued strong performance, with adding new collection points achieving a result 58.95% superior in the long term. S2 consistently outperforms S1 and S3, suggesting it may be an effective method for sustaining engagement and growth over time. Meanwhile, S1 and S3 exhibit similar growth patterns and end values, indicating comparable effectiveness.

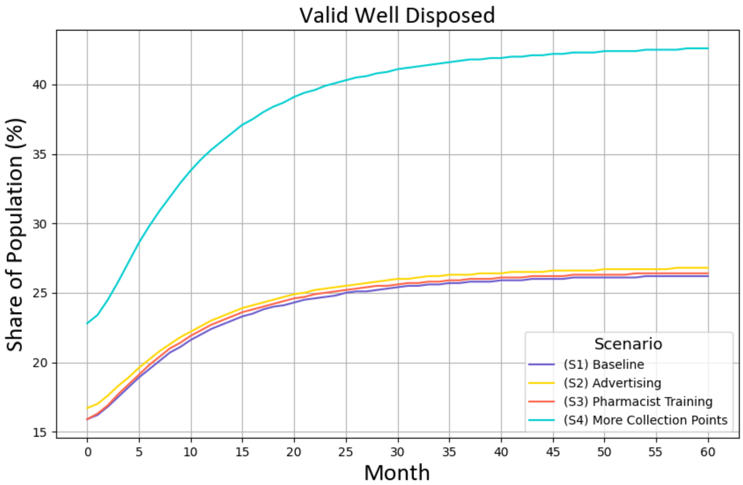

Figure 14: Proper disposal of valid medications

Finally, Figure 15 presents the share of the population disposing of valid medications in pharmacies. Initially, all strategies start at similar levels. Over time, S4 consistently maintains the lowest values, reaching a level 25.9% lower compared to the other scenarios. S1, S2, and S3 show a steady increase in values, with advertising performing slightly better than the other alternatives. It is important to note that the increase in this number does not indicate that consumers are shifting from Misericordias to pharmacies for disposing of valid medications. Instead, it reflects a reduction in the disposal of medications in the garbage, which is a positive outcome, even if it is not the ideal solution socially.

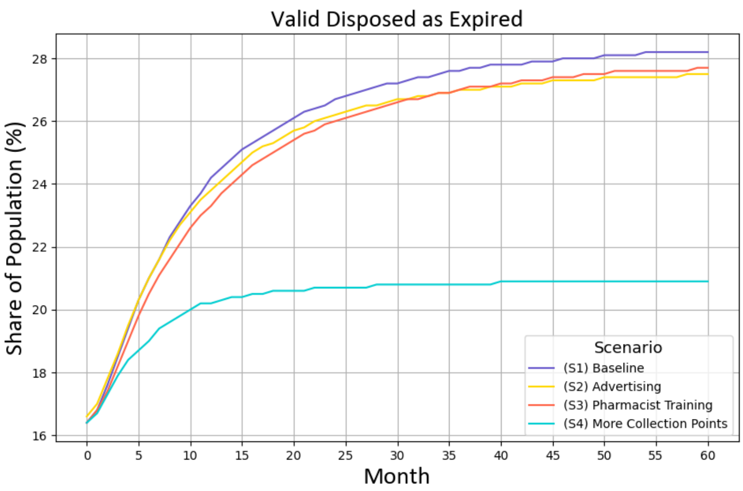

Figure 15: Unproper disposal of valid medication in collection points for expired medications

The results, both for the parameters and for medication disposal, provide interesting insights into the effectiveness of the strategies implemented. Initially, it is observed that none of the alternatives significantly alter the trend of disposing of medications in the garbage. In fact, even without any intervention, societal dynamics and connections alone can reduce the amount of improperly disposed medications. The main change happens specifically with the disposal of valid medications. The most impactful initiative is the introduction of new collection points. This action encourages more people to travel to these points, influencing their social networks. It can be understood that, by reducing the distance and making these collection points more attractive, this initiative fosters connections between individuals, which can alter social attitudes. In fact, literature refer to the accessibility of product collection centers as one of the major factors positively influencing consumer decisions regarding product returns that can compromise the effectiveness of take-back programs (Shi et al., 2023; Ylä-Mella et al., 2015).

Thus, according to the initial population, the results show that environmental benefits will be achieved regardless any specific actions to promote the reduction of improper medication disposal. However, decisions can be made to ensure that valid medications play a significant social role and are disposed of correctly and fairly.

5. Conclusions

Despite properly managing disposal of valid and expired medications is challenging both from environmental and social perspectives, scarce contributions can be found in literature supporting decision and policy makers in evaluating the effectiveness of initiatives in this field. In addition, no studies consider how the impact of these strategies changes according to characteristics of the initial population, as far as authors' knowledge. Accordingly, ABM is used to develop a simulation model that includes agents and parameters crucial to model customers' behavior about disposal of waste medications, as well as initiatives that can be implemented to increase their proper disposal. To illustrate how different strategies can bring different benefits depending on the starting population, real data collected through a survey and a series of interviews are used as input to the simulation model to describe behaviors in a specific geographical area (i.e., Florence, Italy). From a theoretical point of view, our research expands the number of contributions demonstrating the effectiveness of ABM in modelling complex scenarios such as the circular economy. It also presents, for the first time, empirical evidence on its application in the pharmaceutical industry. Considering practical implications, the developed simulation model can be used as decision support tool to identify the more effective strategy according to the initial population. Starting from the current characteristics of both customers and pharmacists, as well as the localization of collection points, some strategies may therefore result more effective than others. Accordingly, local governments (e.g. regions or cities) can therefore compare different initiatives to be implemented to encourage positive behaviors considering the attitudes of the population, which may vary from one area to another, even within the same country.

Besides its valuable contribution to the existing literature, this study reports limitations that set the path for future developments. First, the integration with other simulation techniques (i.e., discrete event simulation or system dynamics) should be evaluated, moving toward the hybrid simulation approach already used in the literature on circular economy, even if in other sectors (e.g., Fani et al. (2022) for fashion rental). In addition, aligned with some authors (Shi et al., 2023) but unlike others (Das and Dutta, 2022; Farida et al., 2023; Ratay and Mohnen, 2022), incentives or rewards to encourage product returns are not taken into consideration here, but can be included especially if the proposed approach is replicated in case of non-expiring products (e.g., appliances and cell phones) or circular business models (e.g., rental services and recycling). Similarly, further development could include other economic aspects, such as the total cost due to circular initiatives in line with the approach followed by (Green et al., 2019), as well as the cost of unused medication proposed by Law et al. (2015). In addition, socio-demographical aspects (such as income, educational level, age, and gender) can be included, as studied in the existing literature (Botelho et al., 2016; Farida et al., 2023). Finally, word of mouth and advice from pharmacists were always considered to have a positive influence on other customers' disposal choices, although the literature is not consistent on this point. For instance, Athern et al. (2016) and Law et al. (2015) state that pharmacists are the ones knowledgeable about the appropriate use of medications and correct behavior regarding medication disposal, as well as the location of medication collection centers in the pharmacy's area, as media services not always report the current recommendations (Petrik et al., 2019). Besides, other studies consider internet and social media as the most reliable sources of information for the proper disposal of medications (Farida et al., 2023; Raja et al., 2022), as evidenced by direct interviews which show that consumers received inappropriate advice from pharmacists or doctors to dispose of or flush their medicines (Tai et al., 2016). Accordingly, misinformation from pharmacists or false advertisements (so-called fake news) should be considered in further studies.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: