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# Promoting Sustainability in an Aging City: Drivers of Proper Pharmaceuticals Disposal

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**Received:** 24 February 2025 | **Revised:** 22 July 2025 | **Accepted:** 13 August 2025

**Funding:** This work was supported by European Commission and the Spanish Ministry of Science, Innovation and Universities, MCIU-19-PCI2019-103676, Ministerio de Ciencia e Innovación, PID2020-115183RB-C21, PID2020-115495RA-I00, PID2022-140010OB-I00, and Gobierno de Aragón, S23\_23R, S40\_23R.

**Keywords:** aging city | bivariate probit models | household pharmaceutical waste | pro-environmental attitudes | sustainability | take-back programs

## ABSTRACT

In a demographic context marked by a rapid increase in the older adult population, pharmaceutical residues represent an increasing threat to sustainability. Promoting the proper disposal of this waste by households is fundamental in attaining the SDGs, particularly SDG 8. This paper assesses the determinants influencing household participation in take-back programs for pharmaceutical waste in an aging city. To this end, we estimate an econometric model where pharmaceutical waste disposal habits are explained by factors grouped into environmental attitudes, socioeconomic factors, and dwelling characteristics. As environmental attitudes include an endogenous factor (individuals' environmental concern), a bivariate probit model is estimated to avoid inconsistent results. The study shows that environmental concern is the most relevant variable and is positively influenced by the knowledge of environmental campaigns and educational level. This research offers a valuable tool for promoting sustainable pharmaceutical waste management, allowing identification of relevant population segments and enabling targeted measures.

## 1 | Introduction

The presence of pharmaceutical residues in the environment represents an increasing threat to sustainability due to the growing rates of production and consumption of medicines<sup>1</sup> and their negative effects on ecosystems and biodiversity (European Commission 2020; Kandasamy et al. 2022; Küster and Adler 2014; Osuoha et al. 2023). A well-documented example of pharmaceutical waste hazards is the development of antimicrobial resistance (AMR) owing to the emergence of multi-drug-resistant microbes, antibiotic-resistant bacteria, and antibiotic-resistant genes (Anwar et al. 2020; Chaturvedi et al. 2021). In 2021, 4.71 million deaths worldwide were related to AMR, of which 1.14 million were estimated to be directly attributable to it (Antimicrobial Resistance Collaborators 2024). Moreover, the number of deaths due to AMR is expected to

rise by 69.6% from 2022 to 2050 (Antimicrobial Resistance Collaborators 2024).

Although collection systems for pharmaceutical waste exist in many countries, household participation remains limited. As such, unused and expired medicines (especially painkillers, antibiotics, or antidepressants) are often stored at home and improperly disposed of with general waste or flushed down the sink or the toilet because individuals are responsible but unclear about proper disposal (Al-Shareef et al. 2016; Gidey et al. 2020; Vogler et al. 2014; Watkins et al. 2022).

This issue is especially relevant in aging urban areas, where pharmaceutical consumption tends to be higher and the volume of medical waste is therefore greater. Moreover, aging can also bring attitudes and habits that limit participation in the proper

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disposal of this waste. Understanding what drives or limits proper disposal in these contexts is essential to improving the design and targeting of sustainability policies.

In this context, promoting the safe disposal of medical waste by households is essential to building more sustainable cities, as it is closely related to several Sustainable Development Goals (SDG) (United Nations [UN] 2015) and specifically with SDG 3, SDG 6, SDG 11, and SDG 12. In addition, improper or non-disposal of unwanted pharmaceuticals hinders sustainable production processes and progress toward a circular economy model by losing opportunities to recycle active ingredients (Hsieh et al. 2017; Kandasamy et al. 2022). Currently, the unavailability of some active ingredients and the resulting medicine shortages are a relevant problem in many countries (Chapman et al. 2022). Promoting circularity in medical waste management is also explicitly related to the SDGs, specifically with SDG 12 and several specific targets of other SDGs, such as 6.3, 8.4, 9.4, and 11.6.

Thus, efficient public policies will be those aimed at promoting the separation of pharmaceutical waste or unused medicines by households and their disposal at the established collection points (Chung and Brooks 2019). This is the case for pharmaceutical collection or take-back programs, which allow people to dispose of their unused medicines at an organized collection site (Bain 2010).

The effectiveness of take-back programs relies on people's participation, so our main objective is to examine the drivers of participation in the take-back programs in Gijón (Spain) to identify the factors that explain household behavior regarding pharmaceutical waste disposal. Understanding these determinants, the study contributes to the design of more effective and better targeted measures to increase participation. The choice of Gijón is relevant for two main reasons. First, because it is a good example of an aging city. In 2022, the median age in Gijón was 50.28 years while its old-age dependency ratio was 44.44<sup>2</sup> (Instituto Nacional de Estadística [INE] 2023). This demographic status quo results in significant long-term care demands, which will likely increase pharmaceutical consumption in the coming years. Second, the Gijón City Council has a take-back program, which allows people to dispose of their unused medicines at pharmacies and four clean points, mainly located at the border of the urban area.

To this end, we employ a database of surveyed households in Gijón to estimate a probit model, where pharmaceutical waste disposal habits are explained by a set of socioeconomic and attitudinal variables, such as age, gender, and environmental concern. However, as the latter is a personal choice, including it directly in the model may introduce an endogeneity problem. Therefore, to obtain an appropriate estimation, a two-equation binary model (bivariate probit model) needs to be specified. This model will allow us to distinguish direct effects (DE) and/or indirect effects (IE) of the regressors on the dependent variable. As far as we know, this approach has not been applied in the study of factors influencing household behavior related to the disposal of pharmaceutical waste.

To address the challenges of improper pharmaceutical waste disposal, we suggest targeted awareness campaigns and nudging

strategies focused on specific demographic groups. These measures can improve household participation in take-back programs and promote sustainable practices.

Moreover, the endogeneity of environmental concern implies recognizing it as shaped by socioeconomic factors and responsive to policy influences, including education and awareness campaigns. This represents an advance over established theories of sustainable behavior frameworks, such as the Theory of Planned Behavior (Ajzen 1991), the Norm Activation Model (Schwartz 1977), and the Value-Belief-Norm theory (Stern et al. 1999), which typically treat it as fixed and exogenous.

This empirical study finds that environmental concern is the main driver of proper pharmaceutical waste disposal among households. Furthermore, it shows that environmental concern is shaped by factors such as education and public awareness campaigns, which influence household behavior indirectly. These results highlight the importance of focusing directly on environmental concern to promote sustainable pharmaceutical waste disposal practices.

In summary, this study has three contributions. First, it employs a bivariate probit model, an econometric technique not previously used in studies on pharmaceutical waste. Second, the endogeneity of environmental concern provides a more dynamic understanding of sustainable behavior, in contrast to established theories that assume environmental concern or values remain stable once formed. Third, by focusing on an aging city like Gijón, where the growth of the older adult population will likely lead to an increase in pharmaceutical waste, the empirical findings can be useful in designing effective take-back programs for this kind of waste to meet the sustainability targets set out in the SDGs and moving toward more sustainable cities.

The remainder of this paper is structured as follows. Section 2 includes a brief review of previous research focused on household disposal of medicines. Next, Section 3 presents the econometric methods, data, and variables used for estimations. In Section 4, we display the main results, while Section 5 discusses the main findings. Finally, Section 6 contains the main conclusions of the empirical study.

## 2 | Literature Review

Previous research indicates that both situational factors (e.g., availability of disposal points) and people's attitudes, influenced by values and social norms, are major drivers of waste sorting and proper disposal (Barr 2004). Take-back programs are a specific tool that has been implemented to tackle situational factors in several cities. These allow people to dispose of their unused medicines at an organized collection site (Bain 2010). However, the effectiveness of these programs still relies on people's predisposition, which depends on situational factors, and people's predisposition are the major drivers of the likelihood of waste sorting and proper disposal (Barr 2004), with the first depending on the availability and access to disposal points, as well as the waste collection fee methods (Welivita et al. 2015; Ezeudu and Bristow 2025). Take-back programs are a specific tool that has been implemented to

tackle situational factors in several cities. These allow people to dispose of their unused medicines at an organized collection site (Bain 2010). However, the effectiveness of these programs still relies on people's predisposition, which depends on educational and intrinsic values (e.g., Barr 2004; Tsai 2008; García-Valiñas et al. 2023), as well as pro-environmental social norms and awareness campaigns (Phillips et al. 2003; Hernández and Martín-Cejas 2005; Dawson and Probert 2007; Tsai 2008; Arena et al. 2021). In this sense, nudging (Thaler 2018) or choice-framing (Johnson et al. 1993; Madrian and Shea 2001) theories have emerged as useful frameworks for increasing predisposition and participation in environmental programs (Sunstein and Reisch 2014). Considering that individuals are subject to cognitive and perception biases may help to design choice environments that increase the effectiveness of standard incentive/mandate-driven strategies at a low cost (Benartzi et al. 2017). To this end, a proper identification of the characteristics of the treated population is paramount to nudge design and the success of measures addressing proper waste disposal (Aprile and Fiorillo 2019; Arbués and Villanúa 2022; Puzzo and Prati 2024); otherwise, undesired effects might emerge due to an unexpected interpretation of the choice architecture–semantic variance – (Selinger and Whyte 2011).

A significant number of studies have been focused on the environmental impact of improper disposal of household unused and expired medicines (Chung and Brooks 2019; Han 2022; Ruhoy and Daughton 2007; Vogler et al. 2014) or on how pharmaceutical waste is discarded by households (Alzayer and Jaromi 2021; Bettington et al. 2018; Gidey et al. 2020; Kusturica et al. 2020), but inadequate attention has been paid to the drivers of household participation in proper pharmaceutical waste disposal (Al-Shareef et al. 2016; Chung and Brooks 2019; Foon et al. 2020; Hajj et al. 2022; Lago et al. 2022; Magagula et al. 2022; Rogowska et al. 2019; Shaaban et al. 2018; Watkins et al. 2022; Xu et al. 2023).

In line with the literature about waste recycling behavior, in these studies can be found two sets of factors: socioeconomic determinants and variables concerning attitudes and knowledge about proper pharmaceutical waste disposal. Within the first group, three variables are commonly used: age, gender, and educational qualification. Occasionally, other variables reflecting different household characteristics, such as income (Hajj et al. 2022), profession (Alomari et al. 2021), number of children (Watkins et al. 2022), or place of residence (Chung and Brooks 2019; Hajj et al. 2022; Magagula et al. 2022), are also included. In the second group, the variables identified can be grouped into three categories: awareness and knowledge of the right medicine disposal options (Chung and Brooks 2019; Foon et al. 2020; Shaaban et al. 2018; Xu et al. 2023), perceptions regarding risks associated with pharmaceutical waste (Dias-Ferreira et al. 2016; Watkins et al. 2022), and social influences (Foon et al. 2020; Watkins et al. 2022; Xu et al. 2023).

The results concerning the influence of socioeconomic variables on the proper disposal of household pharmaceutical waste appear inconclusive. While Al-Shareef et al. (2016) and Watkins et al. (2022) suggest that age is positively related to good disposal practices, others report either no significant relationship

between these variables (Hajj et al. 2022; Lago et al. 2022; Magagula et al. 2022; Shaaban et al. 2018) or a negative relationship (Chung and Brooks 2019). Even Rogowska et al. (2019) obtained contradictory results (positive relationship and non-significance) depending on the sample used. Regarding gender, several studies show that women are more likely to properly dispose of their pharmaceutical waste than men (Al-Shareef et al. 2016; Rogowska et al. 2019; Watkins et al. 2022).

Nevertheless, other works point out that this variable has a negative influence on proper disposal of medicines or is not significant (Lago et al. 2022; Magagula et al. 2022; Shaaban et al. 2018). Finally, the relationship observed between education and proper disposal of pharmaceutical waste appears positive in all studies that include it, except in Rogowska et al. (2019) where an insignificant relationship is found. With regard to behavioral variables, it should be noted that all the empirical studies find that there is a positive association between these kinds of variables and the proper disposal of household pharmaceutical waste.

From a methodological perspective, the most commonly used methods are basic statistical techniques such as the chi-squared test (Al-Shareef et al. 2016; Chung and Brooks 2019; Rogowska et al. 2019; Shaaban et al. 2018), Fisher's exact test (Al-Shareef et al. 2016), and the analysis of variance (ANOVA) (Magagula et al. 2022). It is noteworthy that few studies employ regression-based procedures (Foon et al. 2020; Watkins et al. 2022), which we use in our empirical study. However, unlike these previous works based on a partial least squares methodology, we propose the estimation of a bivariate probit model that allows us to address the endogeneity problem associated with individuals' environmental concern. As far as we know, this approach has not yet been applied in the study of factors influencing household behavior related to the disposal of pharmaceutical waste.

### 3 | Materials and Methods

#### 3.1 | Econometric Strategy

As noted above, our aim is to explain why individuals choose to dispose of their pharmaceutical waste properly. To this end, we define the binary variable  $Med$  that takes the value 1 or 0 depending on whether or not individuals appropriately dispose of their unwanted or unused medicines. Thereafter, we specify a binary response model of the form:

$$p_i = F(\mathbf{x}'_i \boldsymbol{\beta}) \quad (1)$$

where  $p_i$  is the probability of household  $i$  deciding to dispose of their pharmaceutical waste properly, that is,  $p_i = pr(Med_i = 1)$ ;  $F$  is a cumulative distribution function (cdf);  $\boldsymbol{\beta}$  is a vector of parameters; and  $\mathbf{x}_i$  is the vector of regressors for household  $i$ . It is noteworthy that there is a latent model underlying (1), written as:

$$Med_i^* = \mathbf{x}'_i \boldsymbol{\beta} + \mathbf{u}_i \quad (2)$$

where  $Med_i^*$  is a latent variable that can be interpreted as the level of satisfaction linked to the alternative  $Med_i = 1$ . Thus, the relationship between the latent and binary variables is given by:

$$Med_i = \begin{cases} 1 & \text{if } Med_i^* > 0 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Therefore, using (2), we obtain an equivalent form of the binary model (1):

$$Med_i = 1 [\mathbf{x}'_{1i} \boldsymbol{\beta} + \mathbf{u}_{1i} > 0] \quad (4)$$

Depending on whether the cdf function  $F$  of (1) is normal or logistic, the model (1) will be a probit or logit model, respectively. In this paper, we assume  $F = \Phi$ ; therefore, we consider a probit model.

The binary model (1) assumes that regressors in  $\mathbf{x}_{1i}$  are all exogenous. Therefore, the maximum likelihood method would be adequate to estimate the parameter vector  $\boldsymbol{\beta}$ . However, our model includes a binary explanatory variable—environmental concern (*Conc*)—which is expected to be endogenous. Thus, as Wooldridge (2002) argues, the adequate specification is:

$$\begin{aligned} Med_i &= 1 [\alpha Conc_i + \mathbf{z}'_{1i} \boldsymbol{\beta}_1 + \mathbf{u}_{1i} > 0] \\ Conc_i &= 1 [\mathbf{x}'_{2i} \boldsymbol{\delta} + \mathbf{u}_{2i} > 0] \end{aligned} \quad (5)$$

where the error terms  $\mathbf{u}_{1i}$  and  $\mathbf{u}_{2i}$  are jointly distributed as follows:

$$\begin{pmatrix} \mathbf{u}_{1i} \\ \mathbf{u}_{2i} \end{pmatrix} \sim iid N \left( \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix} \right) \quad (6)$$

The parameter vectors of the first equation in (5) is denoted  $\boldsymbol{\beta}' = (\alpha \boldsymbol{\beta}'_1, \mathbf{z}'_{1i})$  being the corresponding vector of regressors. Regressors included in vectors  $\mathbf{z}_{1i}$  and  $\mathbf{x}_{2i}$  are exogenous. Furthermore, Model (5) includes two latent variables,  $Med^*$  and  $Conc^*$ , which underlie the binary variables  $Med$  and  $Conc$  in a similar way to (2).

The overall parameter vector to be estimated in (5) is  $\boldsymbol{\gamma}' = (\boldsymbol{\beta}, \boldsymbol{\delta}', \rho)$ . According to Freedman and Seckhon (2010), it can be estimated by three different procedures: (a) estimation of two single probit models (one for each equation); (b) two-stage estimation; and (c) full maximum likelihood estimation (MLE). The first method is just appropriate when  $\rho = 0$ , that is, when *Conc* is an exogenous variable. However, if  $\rho \neq 0$ , this procedure leads to inconsistent estimates for  $\boldsymbol{\delta}$  and  $\alpha$ , and the two-stage estimator is significantly biased, while MLE is a fundamentally unbiased estimator.

Thus, to choose the adequate estimation procedure, we first need to test the hypotheses:

$$\begin{aligned} H_0: \rho &= 0 \\ H_1: \rho &\neq 0 \end{aligned} \quad (7)$$

The null hypothesis of (7) is the hypothesis of exogeneity. To test it, we first have to estimate model (5) by MLE. The likelihood function to be maximized is written as follows:

$$l(\boldsymbol{\gamma}) = \sum_{i=1}^N (Med_i Conc_i P_i^{m1,c1} + Med_i (1 - Conc_i) P_i^{m1,c0} + (1 - Med_i) Conc_i P_i^{m0,c1} + (1 - Med_i) (1 - Conc_i) P_i^{m0,c0}) \quad (8)$$

where  $P_i^{mj,ck}$  are the joint probabilities corresponding to each combination of the endogenous variables; that is,  $P_i^{m1,c1}$  is  $pr(Med = 1, Conc = 1)$ ,  $P_i^{m0,c0}$  is  $pr(Med = 0, Conc = 0)$ , and analogous meanings are for  $P_i^{m1,c0}$  and  $P_i^{m0,c1}$ . Every joint probability  $P_i^{mj,ck}$  is a bivariate normal cdf, and all of them are summarized as follows:

$$P_i^{mj,ck} = \begin{cases} \Phi(\mathbf{x}'_{1i} \boldsymbol{\beta}, \mathbf{x}'_{2i} \boldsymbol{\delta}, \rho) & \text{if } (j=1, k=1) \\ \Phi(\mathbf{z}'_{1i} \boldsymbol{\beta}_1, -\mathbf{x}'_{2i} \boldsymbol{\delta}, -\rho) & \text{if } (j=1, k=0) \\ \Phi(-\mathbf{x}'_{1i} \boldsymbol{\beta}, \mathbf{x}'_{2i} \boldsymbol{\delta}, -\rho) & \text{if } (j=0, k=1) \\ \Phi(-\mathbf{z}'_{1i} \boldsymbol{\beta}_1, -\mathbf{x}'_{2i} \boldsymbol{\delta}, \rho) & \text{if } (j=0, k=0) \end{cases} \quad (9)$$

Additionally, Monfardini and Radice (2008), following Wilde (2000), affirm that exclusion restrictions are not required but might help in making the estimation results more robust to distributional misspecification. In our context, we consider exclusion restrictions, which requires that  $\mathbf{x}_2$  contains regressors that are not included in  $\mathbf{z}_1$ .

Once we maximize (8) and obtain the estimates of (5), testing exogeneity allows us to decide the best method of estimation. If  $H_0$  in (7) is rejected, *Conc* is endogenous and the adequate estimation procedure is the full MLE. If we do not reject  $H_0$ , *Conc* is an exogenous regressor and we estimate (5) as two one-equational probit models.

There are different procedures for testing exogeneity. Monfardini and Radice (2008) conclude that the LR is the best statistic; even when the assumed distribution of the error term is wrong.

From all previous analyses, we specify model (5) with exclusion restrictions and decide to employ the LR statistic to test for exogeneity, whose expression is:

$$LR = -2(\ell(\tilde{\boldsymbol{\gamma}}_0) - \ell(\tilde{\boldsymbol{\gamma}}))$$

which is asymptotically distributed (under  $H_0$ ) as a  $\chi^2$ . The log-likelihood function  $\ell(\cdot)$ , is evaluated at both the MLE ( $\tilde{\boldsymbol{\gamma}}$ ), obtained by maximizing (8), and the restricted estimate under  $H_0(\tilde{\boldsymbol{\gamma}}_0)$ , which can be obtained as  $\ell(\tilde{\boldsymbol{\gamma}}_0) = \ell(\tilde{\boldsymbol{\beta}}) + \ell(\tilde{\boldsymbol{\delta}})^3$ .

### 3.2 | Marginal Effects

Unlike linear regression models, in binary models, the parameters do not provide the value of the effect of each regressor on the dependent variable. In these models, the sign of the parameters indicates the direction of the change. To obtain the quantitative effect of a change in a regressor on the probability  $p_i$ , we must calculate  $\delta p_i / \delta X_j = f(\mathbf{x}'_{1i} \boldsymbol{\beta}) \beta_j$  if the regressor  $X_j$  is a continuous variable, and  $\Delta p_i = F(\mathbf{x}'_{1i} \boldsymbol{\beta} / X_j = 1) - F(\mathbf{x}'_{1i} \boldsymbol{\beta} / X_j = 0)$  if  $X_j$  is a dummy variable. Given that the effect is different for every observation, the final effect of a change in a regressor on the corresponding probability is obtained by averaging the effects associated with each observation.

According to Christofides et al. (1997), in the context of a bivariate probit model, the effect of a change in a regressor can be usefully evaluated on different probabilities. The most obvious effect to consider is the impact of every explanatory variable on the marginal probabilities. In our case, we denote  $P_i^{m1}$  as the

marginal probability of disposing of unused or expired medicines appropriately, which can be written as the sum of the corresponding joint probabilities, that is:

$$P_i^{m1} = P_i^{m1,c1} + P_i^{m1,c0} \quad (10)$$

On the contrary, the explanatory variables of the first equation in (5) present DE on the joint probability  $P_i^{m1,c1}$ , while the regressors of the second equation have IE on it. If a regressor appears in both equations of (5), it has DE and IE on  $P_i^{m1,c1}$ . The same analysis can be performed on  $P_i^{m1,c0}$ . Therefore, the total effect (TE) of a change in a regressor on the marginal probability  $P_i^{m1}$  will be the sum of the DE and IE on both joint probabilities:

$$TE^{m1} = TE^{m1,c1} + TE^{m1,c0} = (DE^{m1,c1} + IE^{m1,c1}) + (DE^{m1,c0} + IE^{m1,c0}) \quad (11)$$

Finally, it is important to note that the IE over  $P_i^{m1,c1}$  and  $P_i^{m1,c0}$  have the same magnitude but opposite signs; therefore, the TE over  $P_i^{m1}$  will only show the DE.

### 3.3 | Data

The database used in this study comes from a survey carried out in Gijón between December 2020 and April 2021 on a random sample of 1575 households. The participants were asked about their environmental concern and their knowledge of the different environmental awareness programs carried out in Gijón. Moreover, they were asked about the proper disposal of their pharmaceutical waste. Furthermore, the survey included a set of questions related to characteristics of the individuals and dwellings.

### 3.4 | Variable Specification

The dependent variable (*Med*) is a binary variable that represents household attitudes toward proper disposal of their pharmaceutical waste. It takes the value 1 if the respondent answers affirmatively to the question “Do you take out your pharmaceutical waste to the recycling containers?” and 0 otherwise. To explain this variable, we consider a set of potential factors grouped into three categories: environmental attitudes, socioeconomic characteristics, and dwelling characteristics. All variables are summarized in Table 1.

## 4 | Results

### 4.1 | Model Estimation

As mentioned in Section 3, to choose the appropriate estimation procedure, it is necessary to test whether the variable *Concern* is endogenous. To this end, following Monfardini and Radice (2008), the LR test of exogeneity is carried out; the result is shown in Table 2.

As we can see in Table 2, the value of the LR statistic is 27.7486 and the *p* value is 0. According to this result, the null hypothesis must be rejected; therefore, *Conc* is an endogenous regressor in

TABLE 1 | Variables and their definitions.

Variable	Definition
<i>Med</i>	Proper disposal of pharmaceutical waste (yes = 1; otherwise = 0)
Type 1: environmental attitudes	
<i>Conc</i>	Concern about environmental issues (yes = 1; no = 0)
<i>Aw_ppp</i>	Knowledge of the campaign carried out in Gijón to raise awareness on waste disposal (yes = 1; no = 0)
<i>Aw_env</i>	Knowledge of the environmental awareness campaign carried out in Gijón throughout the year (yes = 1; no = 0)
Type 2: individual sociodemographic characteristics	
<i>Male_50</i>	Gender variable (1 if 50% or more of household members are males; 0 otherwise)
<i>H_inc</i>	Income level variable (1 if household earns a monthly income of 3700€ or more; 0 otherwise)
<i>Uni_ed</i>	Educational level variable (1 if the respondent has university education; 0 otherwise)
<i>Av_age</i>	Aging variable (household average age)
Type 3: dwelling characteristics	
<i>Rural</i>	Location variable (1 if household resides in a rural or non-urban area of the municipality; 0 otherwise)
<i>N_dwell</i>	Age of dwelling variable (1 if household lives in a dwelling constructed 10 or fewer years ago; 0 otherwise)
<i>Own</i>	Dwelling ownership variable (1 if household owns the house where they live; 0 otherwise)

Equation (1). Thus, the bivariate model proposed in (5) must be estimated by the ML procedure.

Table 3 shows the ML estimation results of the bivariate probit model (5). It is noteworthy that we can only interpret the

TABLE 2 | Test of endogeneity.

Value of $\hat{\rho}$	Hypotheses	LR test	Distribution	$p$	Conclusion
-1	$H_0: \rho = 0$ $H_1: \rho \neq 0$	27.7486	$\chi^2_1$	0.0	Reject $H_0$

TABLE 3 | Estimated probit bivariate model for proper medicine disposal habits.

First equation of model (5) dependent variable: <i>Medic</i>	
Variable	Coefficients
Constant	-0.158**
Conc	1.655***
Male_50	-0.0819**
N_house	-0.140**
H_inc	0.175***
Rural	0.105**
Uni_ed	-0.151*
Av_age	0.00308***
Second equation of model (5) dependent variable: <i>Concern</i>	
Variable	Coefficients
Constant	-0.380***
Uni_ed	0.272***
Aw_ppp	0.169***
Aw_env	0.263***
Own	-0.131*

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ .

statistical significance and the sign of every estimated parameter. Thus, to determine the magnitude of the effect of every regressor on the probability that households appropriately dispose of their pharmaceutical waste, in the following Section 4.2, we implement the procedure described in Section 3.2.

Regarding factors that have DE on pharmaceutical waste disposal habits (upper side of the table), we observe that all variables are significant at least at 5%, except *Uni\_ed*, which is only significant at 10%. The sign of the coefficient of environmental concern (*Conc*) is positive, implying that fostering environmental concern across households increases the probability of proper disposal of their unused or expired medicines. Other determinants with positive signs are *H\_inc*, *Rural*, and *Av\_age*. Table 3 also shows that households with a majority of males (*Male\_50*) present worse attitudes toward pharmaceutical waste disposal. Similarly, living in modern buildings (*N\_house*) and having university education (*Uni\_ed*) decreases  $\text{pr}(Med = 1)$ .

When we examine the determinants of environmental concern (*Conc*), which are the factors with IE on  $\text{pr}(Med = 1)$ , all of them are significant at 1%, 5%, and 10%, except *Own*, which is only

significant at 10%. While being aware of pro-environmental campaigns and education programs has been proven to raise environmental concern, home ownership negatively influences the environmental concern of individuals. Furthermore, in contrast to the estimation of the second equation of model (5), *Uni\_ed* increases the probability of being environmentally concerned. The total effect of this variable on pharmaceutical waste disposal habits will be explored in the next subsection.

## 4.2 | Estimated Marginal Effects

Table 4 shows the marginal effects of regressors on the probability of proper disposal of pharmaceutical waste ( $P^{m1}$ ). As explained above, the explanatory variables of the first equation of model (5) have DE on  $P^{m1}$  (through  $P_i^{m1,c1}$  and  $P_i^{m1,c0}$ ) and those of the second equation of model (5) have IE on  $P^{m1}$ . Given that *Uni\_ed*, as appears in both equations of (5), has DE and IE on  $P^{m1}$ . The first column in Table 4 shows the TE of the explanatory variables of the model on  $P^{m1}$ . As can be seen, the regressor with the largest total effect on  $P^{m1}$  is *Conc*. More precisely, a respondent who answers that they are somewhat concerned with the environment presents a probability of discarding their medicines in an appropriate manner 0.476 higher than of those who are not concerned.

Regarding the total marginal effect of the remaining exogenous regressors, the probability of discarding their unused or unwanted medicines properly in high-income households (*H\_inc*) is higher by 0.05 than in other households, while those living in rural areas (*Rural*) increase this probability by 0.03 compared to those inhabiting urban spaces. Moreover, one additional year in the average age of the members of a household (*Av\_age*) increases this probability by 0.001.

Among the variables with negative TE, we find that university education (*Uni\_ed*) has the largest total marginal effect; therefore, if the household includes at least one member with university education, the probability of managing their pharmaceutical waste properly decreases by 0.044 compared to households without members with this educational level. Moreover, people living in houses less than 10 years old (*N\_house*) present a probability of disposing of their pharmaceutical waste properly by lower 0.041 than those residing in older houses. Finally, the total marginal effect of *Male\_50* on  $P^{m1}$  shows that in male-dominated households, the probability decreases by 0.024 in comparison with predominantly female households.

## 5 | Discussion

The marginal effects presented in Table 4 show that environmental concern is the most relevant variable in explaining why individuals choose to properly dispose of their unused or expired

**TABLE 4** | Marginal effects of the determinants of medicine proper disposal habits.

Determinants	TE <sup>m1</sup>	DE <sup>m1,c1</sup>	IE <sup>m1,c1</sup>	DE <sup>m1,c0</sup>	IE <sup>m1,c0</sup>
Conc	0.4764*** (35.940)	0.3247*** (26.360)	— —	0.1517*** (16.710)	— —
Male_50	−0.0236** (−2.340)	−0.0041** (−2.340)	— —	−0.0195** (−2.330)	— —
N_house	−0.0408** (−2.170)	−0.0073** (−2.080)	— —	−0.0335** (−2.190)	— —
H_inc	0.0496*** (3.200)	0.0090*** (2.750)	— —	0.0406*** (3.300)	— —
Rural	0.0302** (2.040)	0.0053** (1.990)	— —	0.0249** (2.050)	— —
Uni_ed	−0.0439** (−2.100)	−0.0027*** (−28.153)	0.0363*** (4.170)	−0.0412*** (−66.752)	−0.0363*** (−4.170)
Av_age	0.0009*** (3.530)	0.0002*** (3.160)	— —	0.0007*** (3.530)	— —
Aw_ppp	— —	— —	0.0248*** (3.740)	— —	−0.0248*** (−3.740)
Aw_env	— —	— —	0.0407*** (6.520)	— —	−0.0407*** (−6.520)
Own	— —	— —	−0.0203* (−1.760)	— —	0.0203* (1.760)

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ .

medicines in an appropriate manner. Focusing on this variable (*Conc*), the econometric estimation shows that it has a direct positive impact on behavior toward the proper disposal of pharmaceutical waste. Note that these results are similar to those found in previous studies focused on different types of waste management habits in the household (Arbués and Villanúa 2016; Barr 2004; Nnorom et al. 2009).

Environmental concern is positively influenced by the knowledge of different environmental campaigns and the education level (bottom of Table 4). This implies that, indirectly, these variables influence positively households' decision to properly dispose of their medical waste. This reinforces the importance of developing environmental awareness campaigns and promoting education for sustainable development (Aldeyemi et al. 2025). In this way, collaboration between agents who have the power to influence people (environmental authorities, educational staff, communication media, community managers, etc.) is imperative for improving environmental concern in society and thus encourage households to adopt eco-friendly behaviors (Tang et al. 2020; Heidig et al. 2025). In the case of medical waste, collaboration of producers and pharmacies will be fundamental to reinforce awareness about the sustainability impact of improper disposal of their unused or expired medicines (Law et al. 2015; Rogowska et al. 2019). This collaboration can be carried out by private individuals

voluntarily, by the public sector, or implemented as a part of an extended producer responsibility scheme (ALqodsi 2025). Furthermore, several studies (Bettington et al. 2018; Chung and Brooks 2019; Gidey et al. 2020; Han 2022) have found that the lack of adequate information on how to properly dispose of pharmaceutical waste is one of the main reasons for its improper disposal. Thus, these general programs should be complemented with specific information campaigns focused on how to dispose of unused and expired medicines properly.

The effects obtained for the remaining variables are significant but small; therefore, their influence on households' decision to properly dispose of pharmaceutical waste in an appropriate manner is more limited than environmental concern. Moreover, it is worth noting that the estimated parameters corresponding to *H\_inc*, *Rural*, and *Av\_age* have a positive sign, reinforcing the influence of environmental concern on the probability of properly disposing of unwanted medicines by households.

Focusing on *H\_inc*, this result implies that individuals living in a high-income household are more prone to good disposal practices than those in low-income households. This result supports the findings of Kusturica et al. (2020) and Stoddard et al. (2017), who reported that income is positively related to the willingness to participate in take-back programs for unwanted medicines.

Moreover, this positive relationship is also consistent with previous works on other kinds of waste (Aprile and Fiorillo 2019; Arbués and Villanúa 2022; Yau 2012; Zen et al. 2014).

The probability of embracing good waste disposal practices for unwanted medicines is also higher for respondents living in rural areas. This finding is supported by Dias-Ferreira et al. (2016) and by several studies focused on selective household collection of waste that point out that the accessibility of recycling facilities positively influences the separate waste collection (Arbués and Villanúa 2016; Barr 2004; Stoddard et al. (2017); Zen et al. 2014). As the collection points in Gijón are located on the outskirts, they are more easily accessible to households in the rural areas surrounding the city, making proper disposal of pharmaceutical waste more accessible, as these points are open longer hours than pharmacies (the most accessible collection point in urban areas).

Regarding age, in line with previous works such as Calise et al. (2022) and Watkins et al. (2022), the probability of properly disposing of unused or expired medicines increases as the average age of the household increases. Older people tend to consume more drugs, and their medication regimens also change often; therefore, because they need to visit pharmacies regularly, bringing their unwanted medicines there is not an additional effort. Furthermore, it is very likely that older adults have more time to bring their unwanted medicines to a collection point than younger people because the workday and the presence of children in these households conditions the use of their time. Moreover, this result supports previous works on recycling behavior such as Yau (2012) and Arbués and Villanúa (2022).

The estimated coefficients for *Male\_50*, *Uni\_ed*, and *N\_dwell* are negative. For *Male\_50*, this result is consistent with previous research indicating that women tend to perform more pro-environmental behaviors in their daily activities than men (Kennedy and Dzialo 2015; Xiao and McCright 2014; Smiley et al. 2022). Furthermore, this negative relationship is supported by the fact that in Spain, on average, women spend more time on domestic work and volunteer activities than do men (INE 2022). Regarding the *Uni\_ed* variable, our results are in line with Law et al. (2015), who found that highly educated people showed a lack of consistency and knowledge about how they should safely dispose of their pharmaceutical waste. Thus, in accordance with Law et al. (2015), this inverse relationship may be related, as in the case of e-waste (Cai et al. 2020; Pham et al. 2023), to the fact that people with higher education tend to focus on the macro dimension of environmental problems (as suggested by the positive relationship estimated between this variable and *Conc*), forgetting that more of these problems have their origin at a micro level. That is, while people with university education tend to demonstrate eco-friendly behavior by supporting pro-environmental government actions (e.g., public policies focused on achieving the SDGs), this does not necessarily result in them becoming more involved in specific actions such as the selective disposal of waste (Pham et al. 2023). Moreover, this result is in accordance with the positive coefficient estimated for the *Age* variable. It is noteworthy that in Gijón, 76% of the population with higher education is under 60 years old (INE 2023). Concerning the *N\_dwell* variable, its negative estimated coefficient reflects that people living in recently built dwellings (less

than 10 years old) have a lower probability of properly disposing of their medicines than those living in older dwellings. This result is consistent with the positive coefficients estimated for the *Rural* and *Age* variables, as, on the one hand, the mean age of the dwellings in the rural districts of Gijón is 39.06 years and only 16.06% of them are under 10 years old (INE 2023) and on the other hand, 89.91% of dwellings in Gijón (91.77% in rural districts) that are under 10 years old have nobody over 65 years old living in them (INE 2023).

Last, most of these results suggest that time constraints and inadequate information limit proper disposal of pharmaceutical waste at collection points. These findings lead to two key policy priorities. First, improving accessibility to take-back programs should be addressed by increasing the number and geographic coverage of collection points, extending opening hours, and considering mobile or decentralized collection solutions. Second, targeted communication strategies should be developed to provide clear information on how and where to dispose of unused medicines, with special attention to the groups of people identified as the least likely to engage in proper disposal; that is, younger, urban, and male-dominated households. Both measures should be integrated into broader environmental campaigns and supported by pharmacies and local health authorities to ensure coverage and credibility.

These results show the critical role of environmental concern in promoting proper pharmaceutical disposal. Local authorities should prioritize taking specific measures to address barriers to participation in take-back programs. Thus, since older adults frequently use medicines and are less digitally connected, communication should prioritize non-digital channels such as printed materials, radio, and information points at health centers. In sum, as environmental concern is also a key driver, messages emphasizing the risks of improper disposal may further encourage compliance.

Nevertheless, one important limitation of our empirical strategy is its cross-sectional nature, which conditions the evaluation of how causal relationships evolve over time. Since both environmental concern and pharmaceutical disposal behavior may respond to policy changes or accumulated awareness, future research would benefit from adopting longitudinal or panel data. This would enable the analysis of behavioral and attitudinal change over time, as well as the delayed or cumulative effects of interventions.

## 6 | Conclusion

The accumulation and improper disposal of pharmaceutical waste generates significant hazards to human health and the environment, jeopardizing the achievement of sustainability objectives. Despite efforts to promote more sustainable cities by encouraging households to appropriately dispose of their pharmaceutical waste, few studies empirically studied the factors driving these decisions; as far as we know, none focused on aging urban contexts.

The novelty of this work lies in using a bivariate probit model that addresses the endogeneity of the environmental concern

to examine the factors influencing household participation in a take-back program for unused and unwanted medicines. The results clarify the factors that directly and indirectly influence how households dispose of their pharmaceutical waste. This econometric approach allows us to account for the endogeneity of environmental concern, representing a relevant methodological contribution with respect to previous empirical studies that treat concern as exogenous (Foon et al. 2020; Watkins et al. 2022; Xu et al. 2023).

In addition to these theoretical insights, the results obtained from the empirical study provide valuable information for policymakers and other relevant stakeholders to improve the effectiveness of implemented measures by adapting them to different kinds of households. Furthermore, the results obtained can help to identify the obstacles to safe disposal of pharmaceutical waste. This is valuable because it allows us to design measures to overcome these barriers and improve pharmaceutical waste separation by households. This improvement is crucial to achieve more sustainable cities, especially in a demographic context marked by a rapid increase in the number of older adults (over 65 years) population.

Our results indicate two major ways of action: first, reinforcing environmental awareness campaigns focused on all the stakeholders involved in the pharmaceutical chain, including end-users (patients) and second, making the collection more reachable by increasing the number of accessible collection points, improving the information about how they work (schedules, location, etc.), and their importance for long-term sustainability.

The findings from Gijón (Spain) are also relevant for other cities in Western Europe (e.g., Italy, Germany) and East Asia (e.g., Japan), where the population is aging, and pharmaceutical consumption is increasing with it. Recognizing environmental concern as a modifiable and endogenous factor strengthens its theoretical relevance and supports designing targeted awareness campaigns to enhance participation in take-back programs. For regions where collection infrastructure is more limited, such as some areas of Latin America or Southeast Asia, these results highlight the potential of promoting environmental concern as a first step toward better disposal practices. This reinforces the broader value of treating environmental concern as a policy-responsive factor, in both sustainability planning in general and in pharmaceutical waste management in particular.

This study therefore contributes to bridging some gaps in the literature, especially by introducing a methodology that overcomes limitations of previous works using simple statistical approaches (Chung and Brooks 2019; Hajj et al. 2022; Magagula et al. 2022; Rogowska et al. 2019; Shaaban et al. 2018), and by reconceptualizing environmental concern as a dynamic, policy-sensitive driver of sustainable behavior.

In sum, these findings can help municipal authorities develop targeted strategies: improving physical access to collection points, ensuring clear information at points of use, and adapting communication formats to meet the needs of diverse demographic groups.

Finally, this study has some limitations to be addressed in future research. First, a cross-sectional database was used in the empirical estimation, so the estimated relationships should be interpreted as associations rather than causal effects. As future decisions can be influenced by past practices, it would be useful to carry out a study using a time series or panel dataset. Introducing the temporal dimension would allow us to evaluate the impact of different measures by observing the changes over time in the drivers of household participation in the separate collection of their medicines. Second, this study focused on households from a particular city (Gijón) in a developed country (Spain) with an aging demographic structure. Therefore, it would be valuable to replicate this study in other cities in different countries with different demographic structures to test the robustness of our findings. Additionally, to strengthen the approach adopted, future research could explore alternative specifications of the bivariate model and include interaction effects (e.g., between education and environmental concern) to better address behavioral heterogeneity. Future research could also estimate the model on subsamples (e.g., by age or education level), test sensitivity to alternative variable specifications, and compare the results with those obtained from single-equation models to confirm the added value of the joint estimation strategy. Moreover, robustness checks such as the use of alternative exclusion restrictions, the inclusion of instrumental variables, or comparison with matching-based estimators could further validate the findings. Exploring these alternatives would help assess the sensitivity of results to model assumptions and improve the credibility of policy recommendations.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Endnotes

<sup>1</sup> According to the United Nations Industrial Development Organization [UNIDO] (2024), the pharmaceutical industry increased their share of global manufacturing value added from 3.9% to 7.0% between 2002 and 2022. Furthermore, in that same period the manufacture of basic pharmaceutical products and preparations increased by 24.7% (Eurostat 2024). Regarding consumption, the global use of medicines between 2024 and 2028 is expected to grow at 2.3% per year for the next 5 years, reaching the figure of 3.8 trillion daily doses in 2028 (IQVIA 2024).

<sup>2</sup> According to the OECD (2023), the old-age dependency ratio is defined as the number of older adults as a share of those aged 20 to 64 (working-age people).

<sup>3</sup> Note that  $\tilde{\beta}$  and  $\tilde{\delta}$  are the corresponding separate ML estimation of the two univariate probit equations of (5).

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