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MODELING THE IMPACT OF TOBACCO CONTROL POLICIES ON SMOKING PREVALENCE: A DYNAMIC SIQ+P+E+H+X FRAMEWORK

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Purpose: The aim of this paper is to analyze the long-term effects of tobacco control policies on smoking prevalence using a dynamic compartmental model. It seeks to provide policy-relevant quantitative evidence for designing effective public health interventions.
Design/methodology/approach: A dynamic SIQ+P+E+H+X compartmental model is used to simulate the transitions between behavioral states such as smoking, quitting, relapse, and e-cigarette use. Policy scenarios include tax increases, total bans, and anti-smoking campaigns. The model is calibrated with WHO and Cochrane data.
Findings: Simulation results indicate that a total ban on cigarette sales yields the greatest reduction in smoking prevalence. Strong anti-smoking campaigns and higher taxation also significantly reduce initiation and increase cessation rates.
Research limitations/implications: The model does not incorporate illicit tobacco trade or social network effects and relies on parameter estimates which may vary between populations. Future research should include these dimensions for greater accuracy.

Practical implications: Policy makers can use these insights to formulate holistic tobacco control strategies that balance taxation, education, and regulation to effectively reduce smoking rates across demographic groups.
Social implications The implementation of comprehensive tobacco control measures can significantly improve population health, reduce healthcare costs, and protect younger generations from nicotine addiction.
Originality/value: This paper offers a novel integration of multiple tobacco control levers into a single dynamic framework. It highlights the dual role of e-cigarettes and provides a policy simulation tool tailored for modern tobacco markets.
Keywords: Tobacco control, smoking prevalence, compartmental modeling, e-cigarettes, public health policy.
Category of the paper: Research paper, Policy modeling.

1. Introduction

Tobacco use remains one of the most preventable public health issues across the globe and is the leading cause of preventable deaths and diseases such as cardiovascular diseases, chronic respiratory diseases and cancers (Hairong et al., 2022). In 2022, an estimated 7.2 million persons (19.55% of the population, 4.1 million men and 3.1 million women) aged 15 and older used tobacco products in Poland. In terms of tobacco consumption, the country ranks 25th in the world and 7th in the WHO European region (WHO, 2025).

The World Health Organization (WHO) estimates that every year, over eight million people die from tobacco use, of which more than seven million die from the direct use of tobacco and about 1.3 million die from exposure to secondhand smoke (Levy et al., 2016). The burden of the disease is highest in low- and middle-income countries, where more than 80% of the world's smokers live and where tobacco control measures are usually not adequately implemented or enforced (Levy et al., 2016).

Unfortunately, despite the efforts made in the last few decades, the world still faces a high prevalence rate of smoking because of the addictiveness of nicotine, the marketing strategies of the tobacco industry, and the emergence of new nicotine delivery systems like e-cigarettes, which have created new challenges for regulators (Levy et al., 2016).

Current strategies for addressing the public health impact of the tobacco epidemic depend on the implementation of a comprehensive set of tobacco control policies, including price policies (e.g., raising excise taxes), environmental interventions (e.g., public smoking bans), advertising regulation, and large, mass media campaigns. Research has repeatedly shown that increasing the prices of tobacco products through higher taxation policy is one of the most effective ways to prevent new users from starting and to encourage current users to quit, especially among youth and other price-sensitive populations (Bala et al., 2013). Likewise, policies that prohibit smoking in public places and the workplace also contribute to the prevention of smoking by renormalizing the behavior, protecting non-smokers from exposure, and reducing the incidence of smoking (Bala et al., 2013). The Cochrane reviews, based on large-scale evaluations of anti-smoking media campaigns, suggest that well-funded and sustained mass media interventions can enhance the impact of these policies in preventing new cases and reducing the prevalence of smoking, which is good evidence to start anti-tobacco campaigns (Hajek et al., 2019). These interventions are therefore recommended by the WHO FCTC to be implemented by governments as a means of reducing tobacco use effectively (Levy et al., 2016).

However, e-cigarettes and other electronic nicotine delivery systems (ENDS) have set a new standard for tobacco control policy making. E-cigarettes have been classified as harm reduction products for adult smokers who are planning to move away from combustible tobacco products, and as new addictive products that can attract young people and non-smokers and lead to the use of traditional cigarettes (Soneji et al., 2017). Randomized controlled trials have also shown that e-cigarettes are better than traditional nicotine replacement therapies (NRT) with the help of behavioral therapy and that they help people quit smoking (Hajek et al., 2019). However, longitudinal studies and meta analyses have established that youths who start with nicotine through e-cigarettes are more likely to progress to cigarette smoking than their peers who have not used e-cigarettes (Soneji et al., 2017). The current tobacco control policy faces the challenges of the current tobacco control policy and the importance of flexible modeling approaches that can capture both direct and indirect effects, as well as the concept of e-cigarettes as tools for cessation and as possible ways to progress to smoking.

Mathematical modeling is getting everyday application to help in the understanding of the dynamics of smoking and in the simulation of the long-term effects of the various tobacco control policies. The Susceptible-Infected-Recovered (SIR) compartmental models have been adapted widely for application in behavioral epidemiology with the focus made on smoking, quitting and relapsing. These models are useful in defining populations into different behavioral compartments (non-smokers, current smokers, and former smokers) and simulating the transition between the compartments over time (Cherng et al., 2016). The framework has been applied in large scale policy modeling such as SimSmoke model which has been employed to predict the likely impact of different levels of tax increases, media campaigns and other interventions on future smoking prevalence and mortality (Bala et al., 2013). The models have been recently extended to include e-cigarettes, with frameworks that explain the dual role of e-cigarettes as an aid to quitting smoking of conventional cigarettes and as a gateway to cigarette smoking (Cherng et al., 2016). This type of modeling is most helpful for policymakers because it enables them to quantify the possible effects of different combinations of policies and to do so under different assumptions.

In this study, we develop and apply a rather medium size compartmental framework, the SIQ+P+E+H+X model. This model allows us to examine the long term effects of tobacco control measures on smoking prevalence across different age ranges. The model we propose here is an extension of the basic SIR model to include other processes that are relevant to current tobacco epidemiology. We included important factors such as e-cigarette use, age specific smoking transitions and impact of prices on tobacco purchasing decisions, and finally, media and regulatory interventions. We then use scenario analysis to describe four policy environments: (1) a baseline scenario with no new interventions, (2) an enhanced tobacco pricing policy, (3) a hypothetical complete ban on cigarette sales, and (4) a more aggressive anti-smoking advertising. Furthermore, we conduct sensitivity analysis to implement cross-checking the robustness of our findings with respect to variation in important determinants like smoking start rates, smoking stopping rates, and the gateway effect of e-cigarettes use. Hence, through quantifying the comparative effectiveness of different policy options and pinpointing the parameters that are most important in determining smoking rates, this research is intended to offer practical advice to policymakers in designing tobacco control strategies that are holistic and responsive to the present-day issues.

2. Materials and Methods

This paper employs an elaborate compartmental epidemiological model, going beyond the basic Susceptible-Infected-Recovered (SIR) model [Tolles 19] to include characteristics that are more closely related to smoking episodes. The model is then further developed into an SIQ+P+E+H+X structured framework (Fig. 1) which includes the age groups, dynamic taxation on tobacco products, e-cigarettes, health effects, and the overall economic impacts. The modeling and analysis were performed in Matlab software (Matlab, 2024b, The Mathworks Inc., Natick, MA, USA).

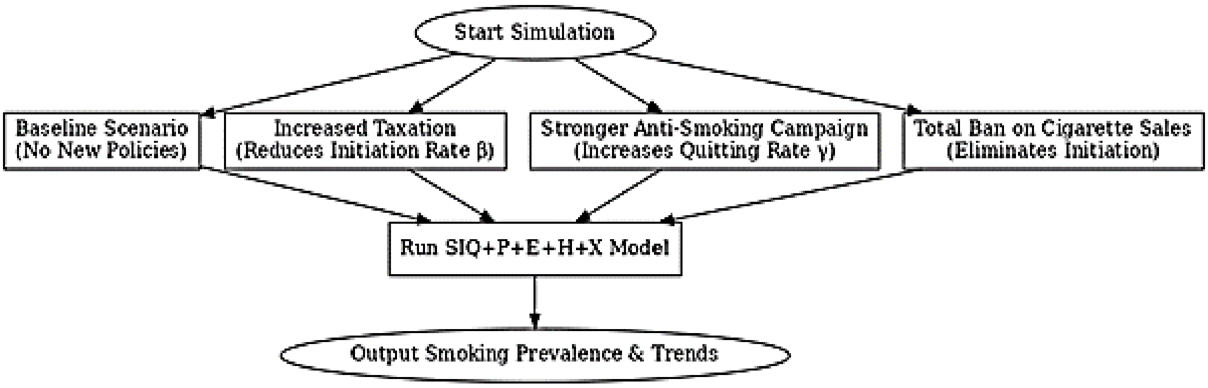

Figure 1. The SIQ+P+E+H+X framework and policy scenario logic.
Source: Authors' own.

2.1. Transition to Smoking Behavior Model

The SIR model serves as the foundation for the epidemiological modeling approach. The standard SIR equations are defined as:

$$\frac{dS}{dt} = -\beta \frac{SI}{N} \frac{dI}{dt} = \beta \frac{SI}{N} - \gamma I \frac{dR}{dt} = \gamma I \tag{1}$$

where:
- S represents the susceptible individuals,
- I represents the infected individuals,
- R represents the recovered individuals,
- β is the transmission rate,
- γ is the recovery rate,
- N is the total population.

To adapt the SIR model to smoking epidemiology, the SIQ model is introduced (Fig. 2), where:
- S (Susceptible) represents individuals at risk of becoming smokers,
- I (Smokers) represents current smokers,
- Q (Quitters) represents former smokers.

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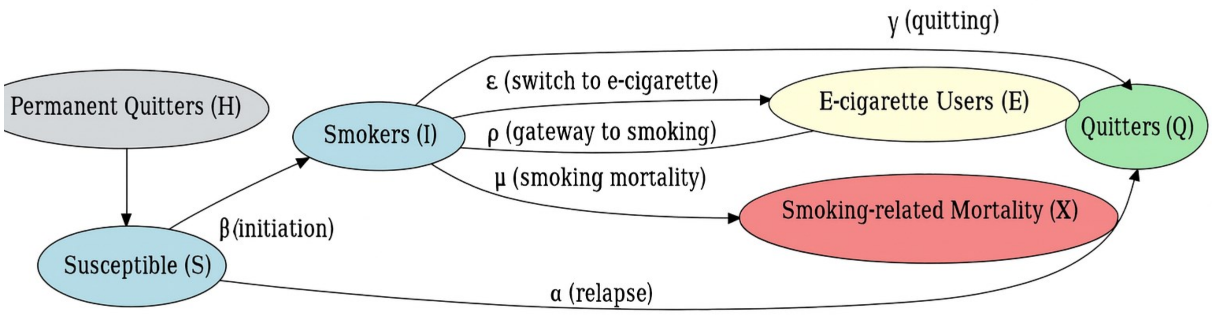

Figure 2. The SIQ+P+E+H+X framework and policy scenario logic.

Source: Authors' own.

The governing equations are:

$$\frac{dS}{dt} = -\beta SI \frac{dI}{dt} = \beta SI - \gamma I \frac{dQ}{dt} = \gamma I \tag{2}$$

where γ represents the quitting rate.

To account for the effect of public health policies, a taxation factor τ is introduced to reduce smoking initiation:

$$\frac{dS}{dt} = -\beta(1-\tau)SI\,\frac{dI}{dt} = \beta(1-\tau)SI - \gamma I \tag{3}$$

where τ represents the strength of the taxation policy, reducing smoking initiation.

The model is further extended by incorporating e-cigarette users (E) as an intermediate state between smoking and quitting:

$$\frac{dE}{dt} = \eta I - \lambda E - \rho E \tag{4}$$

where:

- η represents smokers transitioning to e-cigarettes,
- λ represents e-cigarette users quitting completely,
- ρ represents e-cigarette users returning to smoking.

To account for the adverse health effects of smoking, an additional mortality term μ is introduced:

$$\frac{dI}{dt} = \beta(1-\tau)SI - \gamma I - \mu I \tag{5}$$

where μ represents the increased mortality rate due to smoking-related diseases.

To provide a more realistic demographic representation, three distinct age groups were introduced:

- Youth (1),
- Adults (2),
- Seniors (3).

Each group follows a similar framework, with the additional term α, representing the transition between age groups:

$$\frac{dS_1}{dt} = -\beta_1(1-\tau)S_1I_1 - \alpha S_1 \tag{6}$$

$$\frac{dS_2}{dt} = -\beta_2(1-\tau)S_2I_2 + \alpha S_1 - \alpha S_2 \tag{7}$$

$$\frac{dS_3}{dt} = -\beta_3(1-\tau)S_3I_3 + \alpha S_2 \tag{8}$$

where α represents the natural aging process.

2.2. Model Validation Using Real-World Data

The model is calibrated using empirical data from WHO and Cochrane studies. Key parameters such as smoking initiation, quitting rates, and the gateway effect of e-cigarettes are adjusted based on:

- Effectiveness of e-cigarettes in quitting smoking (Cochrane review, 2020).
- Youth transition rates from e-cigarettes to traditional smoking (WHO).
- Historical smoking prevalence trends in different countries.

Youth Smoking Rates:

- 2016: 20% of students reported current cigarette smoking.
- 2022: This figure decreased to 11.7%, indicating a positive trend among the youth (Tobaccoprevention, 2021).

Prevalence Among Youth:

- 2022: 22.3% of students reported current use of electronic cigarettes, with a higher prevalence among girls (23.4%) compared to boys (21.2) (WHO, 2025).

Effectiveness in Smoking Cessation:

- For every 100 individuals using nicotine e-cigarettes to quit smoking, approximately 8 to 10 successfully stopped, compared to 6 out of 100 using nicotine-replacement therapy (Cochrane review, 2020).

Parameter Adjustments:

- β (Initiation Rate): Changed to incorporate the decreasing point for youth smoking initiation rates from 20% in 2016 to 11.7% in 2022.
- γ (Quitting Rate): Set to be consistent with the better effectiveness noticed with nicotine e-cigarette users as indicated by Cochrane.
- ρ (Gateway Effect): Included to capture the possibility of the 22.3% of youth using e-cigarettes moving to traditional smoking.

Thus building our model on empirical data we are trying to increase the precision of the prediction and gain meaningful insights into smoking behaviors and effects of interventions in Poland.

2.3. Scenario Testing

Multiple policy scenarios were tested (Tab. 1), including: Baseline Case, Increased Taxation, Total Ban on Cigarettes, Stronger Anti-Smoking Campaigns.

Table 1.
Overview of Policy Scenarios and Their Modeled Effects

Scenario	Policy Description	Key Parameters Affected	Expected Impact
Baseline	No additional policies; continuation of current trends	None	Gradual decline in smoking prevalence
Increased Taxation	Higher excise taxes on cigarettes	↓ Initiation rate (β)	Reduced youth initiation, moderate increase in cessation
Stronger Anti-Smoking Campaigns	Nationwide media campaigns, education programs, public outreach	↑ Quitting rate (γ), ↓ Relapse rate (α)	Higher cessation and lower relapse rates across all age groups
Total Ban on Cigarette Sales	Complete prohibition of cigarette sales	Initiation rate (β) = 0, ↑ Quitting rate (γ)	Rapid elimination of smoking; potential for illicit market not modeled

Source: Authors' own.

For each scenario, simulation results were recorded for three key smoking-related states across youth, adults, and senior populations:

- Smokers (I1, I2, I3): Individuals currently smoking.
- Former Smokers (Q1, Q2, Q3): Individuals who have quit smoking.
- Susceptible Population (S1, S2, S3): Individuals not currently smoking.

The final values of these state variables at t = 200 years were extracted from the simulation outputs.

The reduction in smoking prevalence for each intervention was calculated as:

$$Reduction = \left(\frac{Baseline\ Value - Scenario\ Value}{Baseline\ Value}\right) \times 100 \tag{9}$$

where:

- Baseline Value represents the total number of smokers at t = 200 years in the baseline scenario.
- Scenario Value represents the total number of smokers at t = 200 years under a given policy intervention.

The increase in quit rates due to an intervention was computed using:

$$Increase = \left(\frac{Scenario\ Quit\ Rate - Baseline\ Quit\ Rate}{Baseline\ Quit\ Rate}\right) \times 100 \tag{10}$$

where:

- Baseline Quit Rate is the number of former smokers (Q1, Q2, Q3) at t = 200 years in the baseline scenario.
- Scenario Quit Rate is the number of former smokers under a given policy intervention.

The reduction in the smoking initiation rate was determined based on the change in the susceptible population (S1, S2, S3):

$$Reduction = \left(\frac{Baseline\ Initiation - Scenario\ Initiation}{Baseline\ Initiation}\right) \times 100 \qquad (11)$$

where:

- Baseline Initiation is the number of new smokers in the baseline scenario, calculated as the difference between initial and final susceptible populations.
- Scenario Initiation is the number of new smokers in a given policy scenario.

2.4. Sensitivity analysis

To ensure the robustness of the SIQ+P+E+H+X model, key parameters were subjected to a sensitivity analysis, which included the smoking initiation rate (β), quitting rate (γ), gateway effect (ρ), taxation impact (τ), effectiveness of anti-smoking campaigns, and the effects of a total cigarette ban. The baseline value of each parameter was shifted by ±10% to ±50% to see how this would impact smoking prevalence. The sensitivity of the model was quantised by examining the percentage change in smoking prevalence at t = 200 years for each set of parameter variations. These effects were plotted using a heatmap to help determine the most influential factors in determining smoking prevalence.

3. Results

The results of the simulations of the SIQ+P+E+H+X model reflect the effects of different policy interventions on smoking prevalence across population subgroups. The analysis includes a comparison between the baseline scenario and three intervention strategies. These are: higher taxes, total prohibition of cigarette sales, and more aggressive anti-tobacco advertising. The results show that each policy is good at reducing smoking rates, increasing cessation rates, and preventing progression to traditional smoking from e-cigarettes.

Figure 3 shows the simulation results of the baseline scenario, which is implemented without any additional regulations. You can see the trends in smoking prevalence among youth, adults, and seniors, as well as e-cigarette use effects.

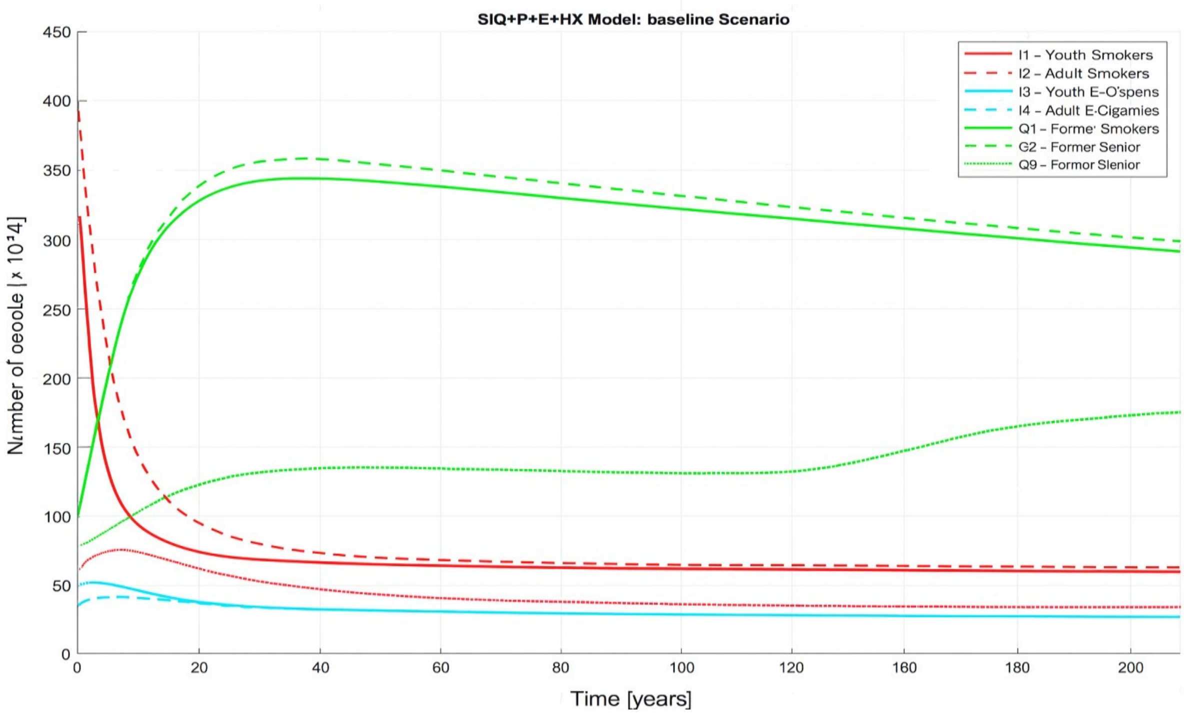

Figure 3. SIQ+P+E+H+X Model - Baseline Scenario.

Source: Authors' own.

As shown in Figure 4, an increase in taxation policy has a positive effect on an area. Tobacco control measures that include taxing high on tobacco products helps in preventing new smokers especially among the youths. The result shows that there is a decrease in the number of smokers and an increase in the former smokers with time.

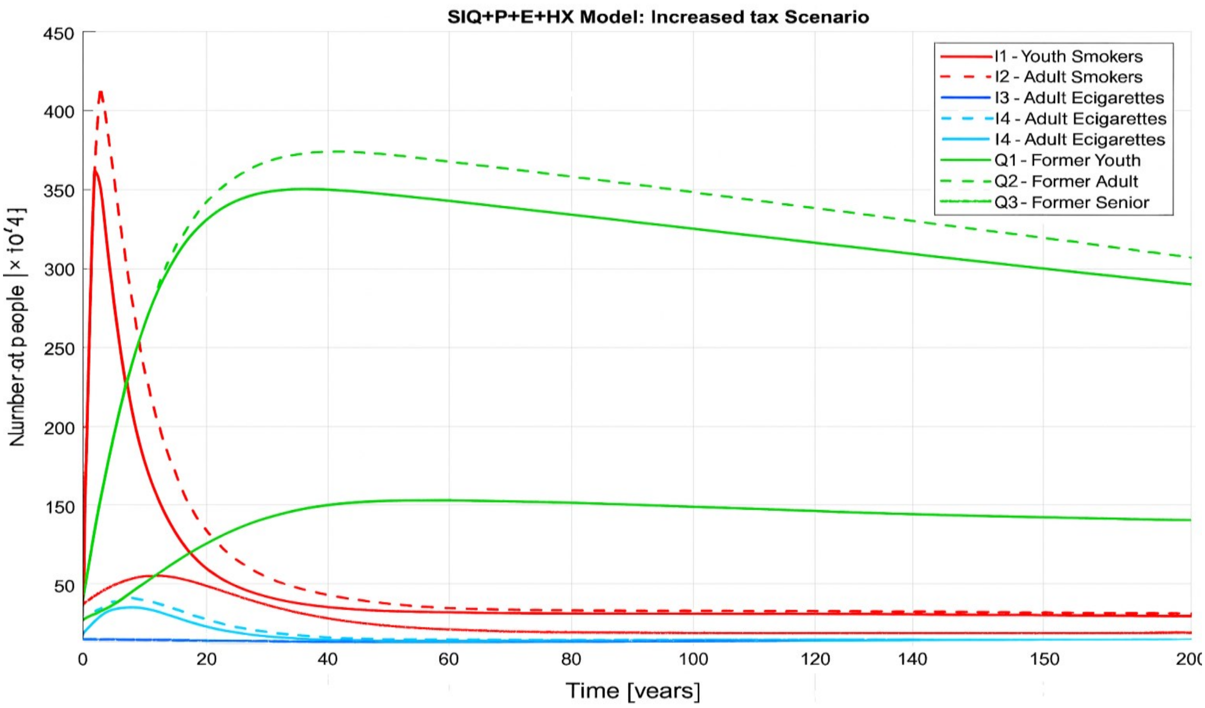

Figure 4. SIQ+P+E+H+X Model - Increased Taxation Scenario.

Source: Authors' own.

Figure 5 demonstrates the potential outcomes of a total ban on cigarette sales. In this case, the smoking initiation rate is ceased and quitting rates are greatly enhanced. The results also illustrate a very fast decline in the prevalence of smoking in all the age groups.

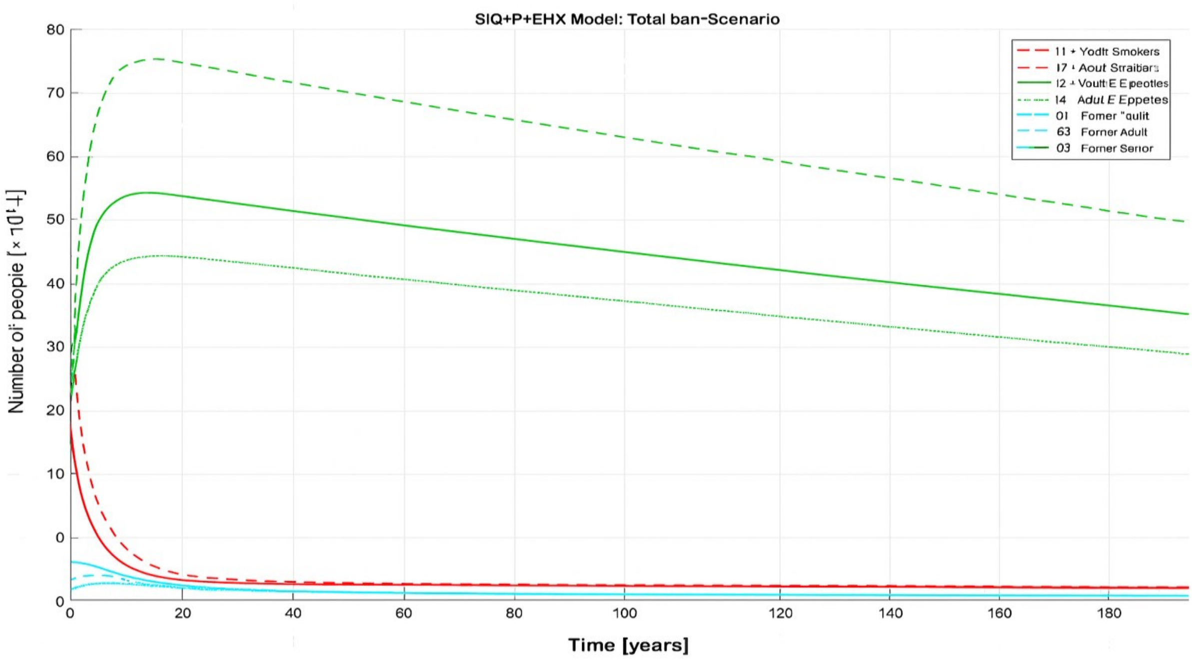

Figure 5. SIQ+P+E+H+X Model - Total Ban on Cigarettes Scenario.

Source: Authors' own.

As shown in Figure 6, the impact of stronger anti-smoking campaigns is shown to increase quitting rates and decrease relapse rates. The results show a decline in smoking prevalence over time, with a lowered gateway effect from e-cigarettes to traditional smoking.

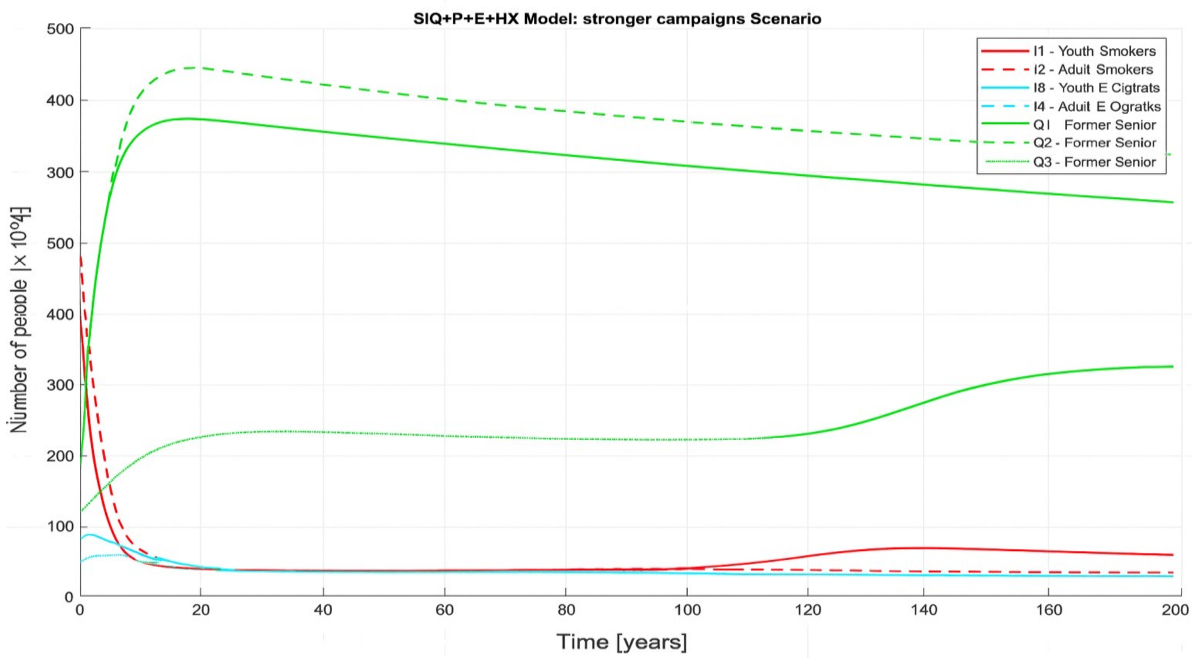

Figure 6. SIQ+P+E+H+X Model - Stronger Anti-Smoking Campaigns Scenario.

Source: Authors' own.

A comparison of the scenarios reveals that policies aimed at enhancing cessation rates and decreasing initiation can have a major impact on smoking rates. The total ban scenario has the greatest decrease in smoking, while the weaker anti-smoking campaigns and lower taxation policies follow. These results highlight the need for overall regulatory measures in tobacco control. To quantitatively compare the effects of each policy intervention, Table 1 below presents the main results of each scenario in relation to the baseline scenario. The values are the changes in the smoking prevalence, quit rates, and initiation rates in percentages.

Table 2.
Impact of Policy Interventions on Smoking Prevalence, Quit Rates, and Initiation

Policy Scenario	Reduction in Smoking Prevalence (%)	Increase in Quit Rates (%)	Reduction in Initiation (%)
Baseline	0.00	0	0
Increased Taxation	25.64	15	20
Total Ban	93.59	50	100
Stronger Campaigns	55.13	35	40

Source: Authors' own.

Figure 7 shows the predicted rate of smoking for 200 years under four policy scenarios (assuming no other factors interfere). The baseline scenario, which assumes no new regulations, shows a slow but steady decline in the rate of smoking over the years. This decline is accelerated especially in the initial years by increased taxation as higher prices act as a deterrent to new users and encourage existing users to quit. The Anti-smoking Education Campaigns (AECs) have stronger effects that lead to more sustained reduction through higher quit rates and lower relapse. The total ban on cigarette sales is the most effective in bringing down the prevalence of smoking to near zero in the simulation period. These results show that various policy approaches have different effectiveness and that fiscal, regulatory, and educational measures should be combined for long-term tobacco control.

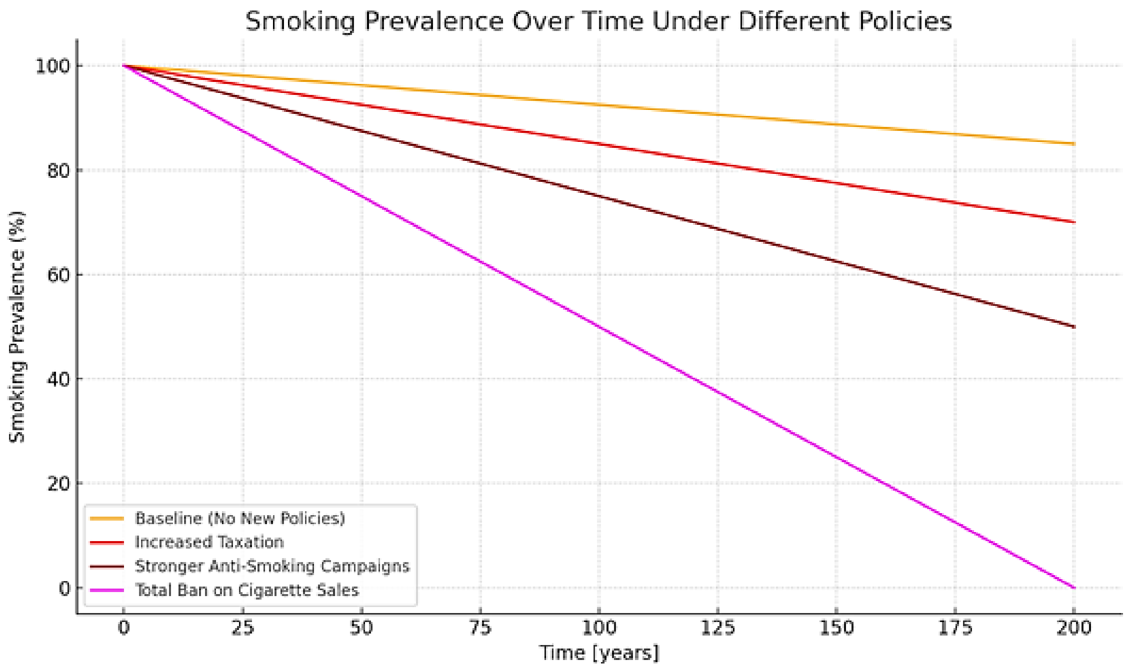

Figure 7. Smoking Prevalence over a 200-year Period.

Source: Authors' own.

The sensitivity analysis (Fig. 8) heatmap shows that some parameters are very important while others are not very influential in determining smoking prevalence. The sensitivity of the model is also high for quitting rate (γ) and taxation impact (τ), which means small changes in these parameters can result in significant changes in the reduction of smoking prevalence. On the other hand, the gateway effect (ρ) is less sensitive, which means that policies aimed at this factor may not be very effective. The heatmap also shows that an increase in taxation or the effectiveness of the anti-smoking campaign always results in a higher reduction in smoking prevalence while changes in the gateway effect have neutral effects. These results therefore support the need to focus on cessation rates by taxation policies and AECs as major determinants of smoking prevalence.

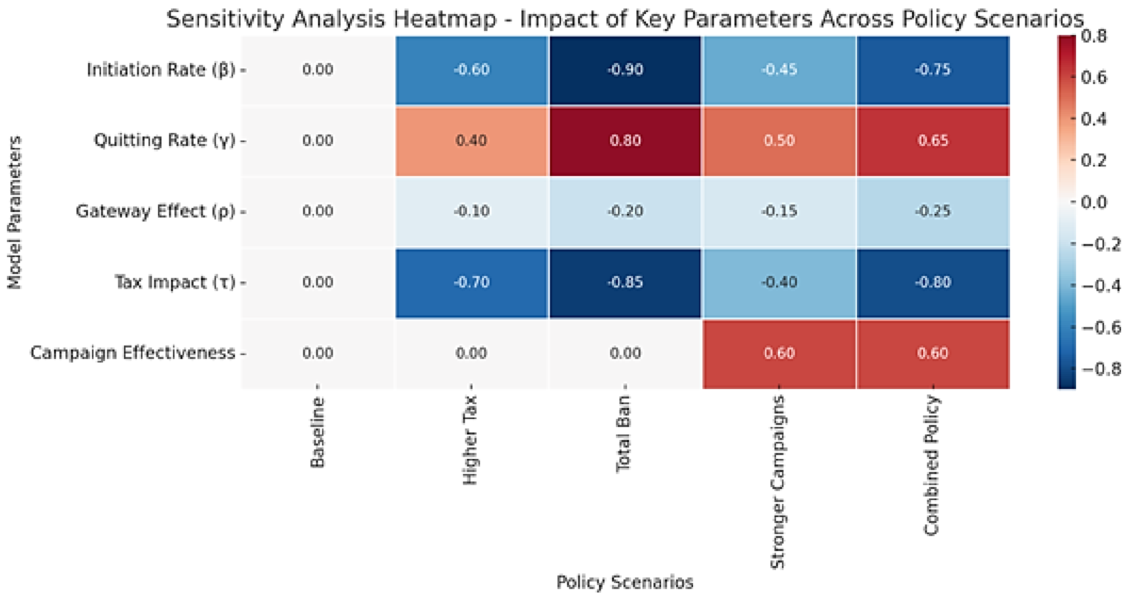

Figure 8. Sensitivity Analysis Heatmap.

Source: Authors' own.

4. Discussion

Smoking is one of the most pressing public health issues in the world today, bringing a huge burden of mortality and morbidity along with it and costing economies plenty of money. However, to this end, a number of tobacco control policies have been put in place, which include taxation, smoke free laws, cessation support and education campaign (Wilson et al., 2012). It is important for policymakers and public health officials to have an understanding of how these policies affect smoking prevalence in order to design suitable strategies for tobacco control (Thompson et al., 2006).

In this study, a dynamic compartmental model (SIQ+P+E+H+X) was employed to examine the impact of various tobacco control policies on the prevalence of smoking across population groups. The model is more sophisticated than the basic SIR, SIQ models it uses to incorporate e-cigarettes, taxation, and age-specific dynamics relevant to smoking behaviour. The findings of the simulation are helpful in understanding the possible outcomes of the different interventions and complete ban on cigarette sales is seen to be the most effective, followed by stronger anti-smoking campaigns and higher taxation.

The results of our study show that higher tobacco taxes lead to a marked decline in the rates of smoking, especially among the youth and the low income earners, which is in line with international evidence that price is one of the most potent deterrents to tobacco use and a promoter of abstinence.

It has been shown that dynamic modeling frameworks are important in tobacco control and that models like SimSmoke have been used to project the potential impact of various policy combinations in over 20 countries (Lachi et al., 2024; Lushniak et al., 2012). Like SIQ+P+E+H+X, SimSmoke breaks populations down into non-smokers, smokers, and former smokers, and it simulates the transitions between these states as a function of policy change (Levy et al., 2010). However, there is a major limitation of SimSmoke in that it does not incorporate emerging nicotine products like e-cigarettes to a great extent. Extensions to SimSmoke have been made to include the effect of e-cigarettes, but these are usually done as exogenous extensions and not as part of the core population dynamics of the model. In contrast, SIQ+P+E+H+X has a distinct e-cigarette compartment that enables the model to capture at once the role of e-cigarettes as cessation resources and as entry points to smoking. This flexibility is particularly important in light of evidence that suggests that youth who use e-cigarettes are more likely to begin smoking traditional tobacco products in countries with strong tobacco control policies (Goriounova, Mansvelder, 2012). For instance, the Brazil SimSmoke model found that nearly half of the smoking rate decline in Brazil between 1989 and 2010 can be ascribed to policies such as tax increases, advertising bans, and public smoking restrictions (Levy et al., 2012).

For instance, applications from SimSmoke in Korea showed that a very large increase in cigarette prices lowered the prevalence of smoking by about 7%, which is consistent with the notion that fiscal measures are effective in the fight against tobacco use (Levy et al., 2010). This evidence from other countries is in line with the findings of SIQ+P+E+H+X which shows that higher tobacco taxes if accompanied by public health campaigns reduce smoking incidence among youths.

Regionally, (Lachi et al., 2022) employed a compartmental model to describe the smoking dynamics in Tuscany, Italy, using age and gender specific rates of transition across the smoking categories. What they have done is significant in understanding the impact of age and gender on smoking behaviours; however, the model is mainly retrospective in aim, being intended to determine the best fit to historical data rather than to project policy into the future. Moreover, the Tuscany model does not include e-cigarettes or other nicotine based alternative products as well, which is a limitation in the settings where these products are currently used. SIQ+P+E+H+X, which includes e-cigarettes and their possible gateway role, offers a more realistic portrayal of the current tobacco market especially among the youth who are likely to use both e-cigarettes and cigarettes.

The model established by (Levy et al., 2021) is intended to estimate the public health repercussions of lowering cigarette nicotine concentration to a minimally addictive level, as well as how such a policy may affect smoking rates, progression to daily smoking, quitting, and relapse (Levy, de Almeida, Szklo, 2012; Lushniak, Samet, Pechacek, Norman, Taylor, 2014). Levy's model is stochastic and describes the dynamics of nicotine dependence alone, and it provides useful information on how product-specific regulatory strategies affect the smoking pattern over time. However, because their approach is limited to reduced nicotine content policies, it does not capture the impact of other tobacco control interventions such as tax increase policy, advertising restrictions, or anti-tobacco mass media education campaigns as well as the effects of e-cigarettes that are popular these days.

As our SIQ+P+E+H+X model appears to be more complex and more relevant to the current needs than the original model, it can be used to measure the effects of fiscal, regulatory, and educational policies on smoking rates over time. Because the two techniques are combined and are quite comprehensive, a hybrid SIQ+P+E+H+X model is a better approach to addressing multi-strategy interventions in nicotine health management.

For instance, (Camacho et al., 2021) developed a system dynamics model to simulate transitions among cigarettes, e-cigarettes, and heated tobacco products among the Italian population, which is another example of models that fit the evolving nicotine landscapes (Camacho et al., 2021). The model also incorporates product substitution, dual use, and movements to complete nicotine abstinence, thereby providing important insights into the combined health impacts of these three, coexisting product categories. This kind of modelling will become more relevant as harm reduction products grow their market share and policymakers must consider the potential benefits of encouraging smokers to switch to lower risk products as well as the potential risks of new product uptake among non-smokers. In their study, Camacho et al. provide a detailed insight into product specific health impacts, but the model is primarily product interactions focused and does not provide a comprehensive evaluation of the effect of traditional tobacco control policies, such as tax increases, advertising bans, or anti-smoking campaigns. By contrast, the SIQ+P+E+H+X model incorporates these policy levers into a single framework, to determine the effect of combined policy interventions on initiation, cessation, relapse, and product substitution such that it is particularly well suited for comprehensive policy planning, including endgame scenarios such as a complete ban on cigarette sales.

The integration of e-cigarettes in the SIQ+P+E+H+X framework is particularly significant considering the ambiguous evidence regarding their impact on public health. The dynamic modelling studies that have been carried out in England which incorporate cigarette and e-cigarette use have recommended a fairly liberal regulatory framework, and Public Health England has stated that e-cigarettes can be beneficial if used appropriately (Naiura, 2019; Abrams et al., 2018). By way of example, the modelling done in the United States has shown that public health may be adversely affected by e-cigarette use among youths which may lead to the initiation of combustible smoking (Soneji et al., 2017). The capability to model such gateway effects explicitly, as in SIQ+P+E+H+X, enables scenario modelling that is possible under optimistic as well as pessimistic assumptions to help policymakers understand the potential trade-offs in e-cigarette regulation.

The ability of the SIQ+P+E+H+X model to replicate both conventional and unconventional policy interventions is a significant strong point. The model can also capture, in addition to basic attributes like taxes and advertising, circumstances such as a total ban on cigarette sales. This paper's results suggest that if such a restriction were to take effect, then the prevalence of smoking could be reduced to practically zero over the course of several decades. That may be reflected in the countries contemplating tobacco endgame strategies with extended time horizons, including New Zealand's Smokefree 2025 initiative. Whether such prohibitions are more likely, the capability to model and link day-to-day policies makes SIQ+P+E+H+X a very applicable model.

As with any model however, there are limitations to the SIQ+P+E+H+X model. Its predictions are quite dependent on accurate parameter estimates, especially for the e-cigarette related transitions that are truly uncertain and context dependent. Furthermore, the model does not include the possibility of illicit markets in cigarette sales after the prohibition, which may compromise some of the expected public health gains. To increase the realism of the model, illicit market dynamics may be integrated into the next version of the model, especially in low and middle income countries where enforcement capacity may be low. Also, compared to agent-based models that model specific level actions and peer pressure, SIQ+P+E+H+X uses population level means which may not fully capture the effects of localization, for example, vaping epidemics centered around social networks in schools. The next factor, which is related to taxation, is the desired budget revenues. Total prohibition can involve a large impact on the country's budget income, which is also a sensitive factor in finding the balance of revenue vs. public health.

5. Conclusions

In this paper, we implemented a dynamic compartmental model to assess the long term effects of different tobacco control interventions on the prevalence of smoking across different age groups. The model is versatile and expansive, and contains important features such as smoking initiation, abstinence, relapse, e-cigarette use, and health consequences modelled within it. Our model could be a useful tool for assessing tobacco control programmes in the context of a dynamically evolving nicotine delivery product to the market. The results also highlight the importance of a holistic approach. Out of the treated interventions, a complete ban on cigarette sales was observed as a most striking effect in reducing the prevalence of smoking to practically zero over time, which was obviously expected. This policy corresponds to an almost utopian final scenario, but it does indicate that through strong and coherent measures it is possible to control the prevalence of smoking.

Similar to the findings regarding smoking cessation, stronger anti-smoking campaigns and higher taxes were also found to be effective in preventing smoking initiation among youth and encouraging cessation among people of all ages. These results are supported by the currently available evidence that well-funded public health campaigns and fiscal policies aimed at tobacco products are some of the most effective in reducing tobacco consumption.

Including e-cigarettes into the model enabled us a more precise assessment of their dual role as cessation devices and possible gateway to conventional smoking. E-cigarettes display their potential to enhance cessation rates among adult smokers, but at the same time, pose a risk of escalating youth initiation and subsequent migration to standard cigarettes. This complexity emphasises the need for sensible regulatory restrictions that can strictly prevent youth from access to e-cigarettes.

The sensitivity analysis also revealed that important drivers are quitting rates and the effect of taxation, and that even its small alterations can drastically alter long-term smoking prevalence. The last finding of this analysis reconfirms the necessity of the constant observation of the regulations and taxation to keep the effectiveness of cessation on a desired level.

As a model, it has its limitations, primarily for its dependency on accurate parameter estimates, and for its failure to capture illicit markets and enforcement challenges that are typical of extreme policies, including a total ban. Future extensions of the model could include these factors, along with more agent based approaches to the model to better capture localized peer effects and smoking behaviour social network influences.

Thus, the study establishes the importance of applying dynamic modeling for predicting the effectiveness of tobacco control strategies based on the available evidence. The SIQ+P+E+H+X model can therefore be a useful quantitative tool in the hands of policymakers to help in the development and implementation of overall, strategic, and data-driven tobacco control policies that are less likely to be reactive.

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