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Research Article

Stability Analysis of an Alcoholism Model with Public Health Education and NSFD Scheme

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In this paper, an alcoholism model of SEAR type with different susceptibilities due to public health education is investigated, with the form of continuous differential equations as well as discrete differential equations by applying the Mickens nonstandard finite difference (NSFD) scheme to the continuous equations. Threshold dynamics of the continuous model are performed by constructing Lyapunov functions. The analysis of a discrete model indicates that the alcohol-free equilibrium is globally asymptotically stable if the basic reproductive number $\mathscr{R}_0 < 1$, and conversely, the alcohol-present equilibrium is globally asymptotically stable if $\mathscr{R}_0 > 1$, revealing the consistency and efficiency of the discrete model to preserve the dynamical properties of the corresponding continuous model. In addition, stability preserving and the impact of the parameters related with public health education are conducted by numerical simulations.

1. Introduction

Alcohol abuse is a major public health concern due to its potential negative health and social effect, especially among college students. There was evidence showing that more than 40% of college students have experienced alcoholism [1, 2], and it has been observed that binge drinking and drinking behaviors have caused negative effects in different levels on students' academic study, social relations, risk-taking, and health [3, 4]. Particularly, alcohol-related injuries and deaths per 100,000 college students increased by 6% from 1998 to 2001 [5]. Studies have shown that alcoholics are more likely to engage in risky behaviors that may result in serious consequences, such as sexually transmitted infections (STIs) [6]. Although much attention has been paid to the reduction in initiation and maintenance of alcohol consumption, the management of such problems in youths still faces a challenge in many countries.

In an attempt to address some of the issues encountered in alcohol control and gain insights into drinking dynamics, many theoretical studies have been carried out by formulating mathematical models that focus on different issues [6–11]. According to the fact that social factors play an important role in modelling the spread of diseases, a number of studies have captured the impact of social interactions on the dynamics of alcohol drinking [8, 12–17]. Benedict presented an SAR-type model with standard incidence to describe alcoholism and studied the existence and stability of the equilibria [12]. In consideration of low-risk and high-risk social transmission process, the authors found that the social interaction between light drinkers and moderate drinkers in a low-risk environment may weaken the significance of the influence of heavy drinking on the disease [16]. Mulone and Straughan in [8] investigated a model for binge drinking in particular with two types of alcoholics and studied the threshold dynamics, which was extended by including the possibility of complete recovery from alcohol dependence in [9]. Different from the assumption of equal infectivity in [8], Huo and Song made a modification of taking into account the different infectious risks of alcoholics in the modelling [14]. In view of alcohol abuse among students on and around college campuses, there have been compartmental models established to study the role of environmental factors on the dynamics of this specific drinking group [13, 15]. Other social behaviors of individuals in the epidemic population, such as treatment, migration, and public health education campaign, have been also incorporated in models to analyze epidemics [18, 19] and alcohol drinking [10, 20–22].

In the literature, different approaches to modelling alcoholism have been used, including continuous ordinary differential equation models [7, 10, 20], partial differential equation models [11, 23], stochastic differential equation model [13], and network models [24, 25]. Meanwhile, the discrete model, with its obvious advantage of describing epidemiology [26–28], can also be employed to understand the process of drinking, which is rarely seen in the abovementioned references. Hence, based on the framework of the SAR-type model, we construct two models with the form of continuous differential equation and discrete differential equation, respectively. In terms of the discretization, the Mickens method is adopted for its efficiency in preserving the global asymptotic stability of equilibria to the corresponding continuous model [29, 30], which has attracted much attention [31–34]. On the contrary, it is known that the function form of the incidence rate in the epidemic model has a crucial role in determining the qualitative behavior of the proposed model and in giving a reasonable description of the dynamics. To account for the influence of public health education on the transmission of alcohol consumption, a general nonlinear incidence is utilized in our models, which is different from that in [20].

The organization of this paper is as follows. In Section 2, we construct and analyze the continuous model. The corresponding discrete model by applying Mickens nonstandard finite difference method is established and conducted in Section 3. In Section 4, numerical simulations are carried out to illustrate the stability preserving and the effect of educational campaigns, and a brief conclusion is given in Section 5.

2. Continuous Drinking Model

2.1. Model Formulation. According to the drinking status, we divide the host population into four categories, i.e., susceptible drinkers $S(t)$, who drink moderately and are susceptible to becoming alcoholic without public health education; educated drinkers $E(t)$, who are susceptible drinkers with public health education; alcoholics $A(t)$, who have drinking problems or addictions; and nondrinkers $R(t)$, who quit drinking or never have drinking problems. Let $N(t)$ denote the total number of all individuals at time t, i.e., $N(t) = S(t) + E(t) + A(t) + R(t)$. In the modelling, we make some assumptions as follows (see [20]):

(i) A1: the recruitment is given by a constant flux Λ, which can enter into the nondrinker class R with proportion of q and the rest $(1-q)\Lambda$ into the susceptible class S

(ii) A2: the susceptible individuals in S can move into the educated class E due to their knowledge by public health education, and individuals in these two classes can be both affected by alcoholics, but with different rates

(iii) A3: alcoholics in A can become nondrinkers because of some factors, such as counselling, treatment, and prohibition

With these assumptions, we have the following system of continuous ordinary differential equations:

$$\begin{cases} \dfrac{dS(t)}{dt} = (1-q)\Lambda - \beta S(t) f(A(t)) - (\mu_S + p)S(t), \\ \dfrac{dE(t)}{dt} = pS(t) - \sigma\beta E(t) f(A(t)) - (\mu_E + \varepsilon)E(t), \\ \dfrac{dA(t)}{dt} = [S(t) + \sigma E(t)]\beta f(A(t)) - (\mu_A + \gamma)A(t), \\ \dfrac{dR(t)}{dt} = q\Lambda + \gamma A(t) + \varepsilon E(t) - \mu_R R(t). \end{cases} \tag{1}$$

In this model, parameter σ is used to denote the infectiousness of educated individuals relative to susceptible ones, which reveals the effectiveness of public health education. $\sigma = 0$ implies that the education is completely effective and $\sigma = 1$ accounts for its useless. β is the transmission coefficient. p denotes the rate moving from the susceptible to the educated class. The individuals in the educated class move to the nondrinker class at a rate ε, and the alcoholics can recover at a rate γ to the nondrinker class. μ_S, μ_E, μ_A, and μ_R denote the death rates in the susceptible, educated, alcoholic, and nondrinker class, respectively. In model (1), to give the incidence rate, we employ a general function $f(A)$, which is sufficiently smooth and is assumed to satisfy the following conditions:

(iv) A4: $f(0) = 0$ for $A = 0$ and $f'(A) > 0$, $f''(A) \le 0$ for $A \ge 0$.

The assumptions for $f(A)$ are fundamental and biologically motivated, and it is easy to check that the function satisfying the above conditions includes the bilinear and the saturation incidences. Note that the variable R in model (1) does not appear in other equations, and thus, the R equation will be neglected in the remaining analysis. The dynamics of the following system without the R equation would be the same:

$$\begin{cases} \dfrac{dS(t)}{dt} = (1-q)\Lambda - \beta S(t) f(A(t)) - (\mu_S + p)S(t), \\ \dfrac{dE(t)}{dt} = pS(t) - \sigma\beta E(t) f(A(t)) - (\mu_E + \varepsilon)E(t), \\ \dfrac{dA(t)}{dt} = [S(t) + \sigma E(t)]\beta f(A(t)) - (\mu_A + \gamma)A(t). \end{cases} \tag{2}$$

All the parameters in system (2) are nonnegative, and we are interested in those nonnegative solutions. It is easy to show that the solution of system (2) with nonnegative initial values is nonnegative and exists for all $t \ge 0$. From the first equation of (2), we have

$$\lim_{t \longrightarrow \infty} \sup S(t) \le \frac{(1-q)\Lambda}{\mu_S + p}. \tag{3}$$

Furthermore,

$$(S+E+A)' \le (1-q)\Lambda - \mu(S(t)+E(t)+A(t)), \tag{4}$$

with $\mu = \min\{\mu_S, \mu_E+\varepsilon, \mu_A+\gamma\}$, and we can study the dynamical behavior of system (2) in the positively invariant set:

$$\Omega := \left\{(S,E,A) \in \mathscr{R}_+^3 \colon 0 \le S \le \frac{(1-q)\Lambda}{\mu_S+p}, 0 \le (S+E+A) \le \frac{(1-q)\Lambda}{\mu}\right\}. \tag{5}$$

It is easy to see that model (2) always has a alcohol-free equilibrium $P_0 = (S_0, E_0, 0)$ with $S_0 = ((1-q)\Lambda)/(\mu_S+p)$ and $E_0 = (p(1-q)\Lambda)/((\mu_E+\varepsilon)(\mu_S+p))$. Define the basic reproductive number as

$$\mathscr{R}_0 = \frac{\beta f'(0)(S_0+\sigma E_0)}{\mu_A+\gamma}, \tag{6}$$

which gives the expected number of secondary cases produced in a completely susceptible and educated population by a typical alcoholics during the time he spends in the infectious period. Then, the alcohol-present equilibrium $P^* = (S^*, E^*, A^*)$ exists if $\mathscr{R}_0 > 1$, where

$$S^* = \frac{(1-q)\Lambda}{\beta f(A^*)+\mu_S+p}, \qquad E^* = \frac{p(1-q)\Lambda}{(\beta f(A^*)+\mu_S+p)(\sigma\beta f(A^*)+\mu_E+\varepsilon)}. \tag{7}$$

Indeed, the alcohol-present equilibrium satisfies the following equations:

$$\begin{cases} (1-q)\Lambda = \beta S^* f(A^*) + (\mu_S+p)S^*, \\ pS^* = \sigma\beta E^* f(A^*) + (\mu_E+\varepsilon)E^*, \\ (\mu_A+\gamma)A^* = (S^*+\sigma E^*)\beta f(A^*). \end{cases} \tag{8}$$

The expression of S^* can be directly obtained by the first equality and E^* by the second in (8), and then it follows from the last equality that A^* remains positive for all $\mathscr{R}_0 > 1$.

2.2. Stability Analysis. In this subsection, the globally asymptotic stabilities of P_0 and P^* will be discussed by constructing suitable Lyapunov functions.

Theorem 1. *If $\mathscr{R}_0 < 1$, then the alcohol-free equilibrium P_0 is globally asymptotically stable.*

Proof. Firstly, we use the Hurwitz criterion to discuss the local stability of P_0. The characteristic equation at P_0 is

$$\begin{vmatrix} \lambda+(\mu_S+p) & 0 & \beta S_0 f'(0) \\ -p & \lambda+(\mu_E+\varepsilon) & \sigma\beta E_0 f'(0) \\ 0 & 0 & \lambda+(\mu_A+\gamma)-(S_0+\sigma E_0)\beta f'(0) \end{vmatrix} = 0, \tag{9}$$

which has three eigenvalues

$$\begin{aligned} \lambda_1 &= -(\mu_S+p), \\ \lambda_2 &= -(\mu_E+\varepsilon), \\ \lambda_3 &= (S_0+\sigma E_0)\beta f'(0) - (\mu_A+\gamma). \end{aligned} \tag{10}$$

It is clear that $\lambda_3 < 0$ when $\mathscr{R}_0 < 1$, then P_0 is locally stable.

Define a Lyapunov function:

$$L_{P_0} = \frac{1}{\mu_A+\gamma}\left\{S - S_0 - S_0 \ln\frac{S}{S_0} + E - E_0 - E_0 \ln\frac{E}{E_0} + A\right\}. \tag{11}$$

Calculating the derivative of L_{P_0} along the solution of system (2), we can obtain

$$\begin{aligned} L'_{P_0} = \frac{1}{\mu_A+a+\gamma}\Bigg\{&\left(1-\frac{S_0}{S}\right)[(1-q)\Lambda - \beta S f(A) - (\mu_S+p)S] \\ &+\left(1-\frac{E_0}{E}\right)[pS - \sigma\beta E f(A) - (\mu_E+\varepsilon)E] \\ &+[(S+\sigma E)\beta f(A) - (\mu_A+\gamma)A]\Bigg\}. \end{aligned} \tag{12}$$

Note that $(1-q)\Lambda = (\mu_S+p)S_0$ and $pS_0 = (\mu_E+\varepsilon)E_0$, then L'_{P_0} can be written as

$$\begin{aligned} L'_{P_0} &= \frac{1}{\mu_A+\gamma}\left\{(\mu_S+p)S_0\left(2-\frac{S_0}{S}-\frac{S}{S_0}\right) + (\mu_E+\varepsilon)E_0\left(2-\frac{E_0}{E}-\frac{E}{E_0}\right) + pS_0\left(\frac{S}{S_0}-1-\frac{E_0 S}{E S_0}+\frac{E}{E_0}\right) + \beta S_0 f(A)\right. \\ &\quad \left. + \sigma\beta E_0 f(A) - (\mu_A+\gamma)A\right\} \\ &= \frac{1}{\mu_A+\gamma}\left\{\mu_S S_0\left(2-\frac{S_0}{S}-\frac{S}{S_0}\right) + (\mu_E+\varepsilon)E_0\left(3-\frac{S_0}{S}-\frac{E}{E_0}-\frac{SE_0}{S_0 E}\right) + \beta S f(A)\left(1-\frac{S_0}{S}\right) + \beta S_0 f(A) + \sigma\beta E_0 f(A) - (\mu_A+\gamma)A\right\} \\ &\le \frac{1}{\mu_A+\gamma}\left\{\mu_S S_0\left(2-\frac{S_0}{S}-\frac{S}{S_0}\right) + (\mu_E+\varepsilon)E_0\left(3-\frac{S_0}{S}-\frac{E}{E_0}-\frac{SE_0}{S_0 E}\right)\right\} + \frac{1}{\mu_A+\gamma}[\beta S_0 f'(0)A + \sigma\beta E_0 f'(0)A - (\mu_A+\gamma)A] \\ &= \frac{1}{\mu_A+\gamma}\left\{\mu_S S_0\left(2-\frac{S_0}{S}-\frac{S}{S_0}\right) + (\mu_E+\varepsilon)E_0\left(3-\frac{S_0}{S}-\frac{E}{E_0}-\frac{SE_0}{S_0 E}\right)\right\} + (\mathscr{R}_0-1)A. \end{aligned} \tag{13}$$

Notice the fact

$$2-\frac{S_0}{S}-\frac{S}{S_0}\le 0,$$
$$3-\frac{S_0}{S}-\frac{E}{E_0}-\frac{SE_0}{S_0E}\le 0, \tag{14}$$

for all $S, E>0$ and the equalities hold if and only if $S=S_0$ and $E=E_0$. Hence, we have $L'_{P_0}\le 0$ when $\mathscr{R}_0<1$ and $L'_{P_0}=0$ only at P_0, which leads to the global stability of P_0. This completes the proof. □

Theorem 2. *If $\mathscr{R}_0>1$, the alcohol-present equilibrium P^* is globally asymptotically stable.*

Proof. Construct a Lyapunov function as follows:

$$L_{P^*}=S-S^*-S^*\ln\frac{S}{S^*}+E-E^*-E^*\ln\frac{E}{E^*}+A-A^*-A^*\ln\frac{A}{A^*}. \tag{15}$$

Then, the time derivative of L_{P^*} along the solution of (2) satisfies

$$\begin{aligned}L'_{P^*}&=\left(1-\frac{S^*}{S}\right)[(1-q)\Lambda-\beta Sf(A)-(\mu_S+p)S]\\&+\left(1-\frac{E^*}{E}\right)[pS-\sigma\beta Ef(A)-(\mu_E+\varepsilon)E]\\&+\left(1-\frac{A^*}{A}\right)[(S+\sigma E)\beta f(A)-(\mu_A+\gamma)A].\end{aligned} \tag{16}$$

Noticing that

$$\begin{aligned}(1-q)\Lambda&=\beta S^*f(A^*)+(\mu_S+p)S^*,\\pS^*&=(\mu_E+\varepsilon)E^*+\sigma\beta E^*f(A^*),\end{aligned} \tag{17}$$

we have

$$\begin{aligned}L'_{P^*}&=(\mu_S+p)S^*\left(2-\frac{S^*}{S}-\frac{S}{S^*}\right)+\left(1-\frac{S^*}{S}\right)(\beta S^*f(A^*)-\beta Sf(A))+(\mu_E+\varepsilon)E^*\left(2-\frac{E^*}{E}-\frac{E}{E^*}\right)+pS^*\left(\frac{S}{S^*}-1-\frac{E^*S}{ES^*}+\frac{E^*}{E}\right)\\&+\left(1-\frac{E^*}{E}\right)(\sigma\beta E^*f(A^*)-\sigma\beta Ef(A))+\left(1-\frac{A^*}{A}\right)\left\{\beta Sf(A)+\sigma\beta Ef(A)-[\beta S^*f(A^*)+\sigma\beta E^*f(A^*)]\frac{A}{A^*}\right\}\\&=\mu_SS^*\left(2-\frac{S^*}{S}-\frac{S}{S^*}\right)+(\mu_E+\varepsilon)E^*\left(3-\frac{S^*}{S}-\frac{E}{E^*}-\frac{SE^*}{S^*E}\right)+\beta S^*f(A^*)\left(2-\frac{S^*}{S}-\frac{Sf(A)A^*}{S^*f(A^*)A^*}+\frac{f(A)}{f(A^*)}-\frac{A}{A^*}\right)\\&+\sigma\beta E^*f(A^*)\left(3-\frac{S^*}{S}-\frac{SE^*}{S^*E}-\frac{Ef(A)A^*}{E^*f(A^*)A}+\frac{f(A)}{f(A^*)}-\frac{A}{A^*}\right)\\&=\mu_SS^*\left(2-\frac{S^*}{S}-\frac{S}{S^*}\right)+(\mu_E+\varepsilon)E^*\left(3-\frac{S^*}{S}-\frac{E}{E^*}-\frac{SE^*}{S^*E}\right)+\beta S^*f(A^*)\left[-g\left(\frac{S^*}{S}\right)-g\left(\frac{Sf(A)A^*}{S^*f(A^*)A}\right)+\frac{f(A)}{f(A^*)}-\frac{A}{A^*}\right]\\&+\sigma\beta E^*f(A^*)\left[-g\left(\frac{S^*}{S}\right)-g\left(\frac{SE^*}{S^*E}\right)-g\left(\frac{Ef(A)A^*}{E^*f(A^*)A}\right)+\frac{f(A)}{f(A^*)}-\frac{A}{A^*}\right]\\&=\mu_SS^*\left(2-\frac{S^*}{S}-\frac{S}{S^*}\right)+(\mu_E+\varepsilon)E^*\left(3-\frac{S^*}{S}-\frac{E}{E^*}-\frac{SE^*}{S^*E}\right)+\beta S^*f(A^*)\left[-g\left(\frac{S^*}{S}\right)-g\left(\frac{Sf(A)A^*}{S^*f(A^*)A}\right)-g\left(\frac{Af(A^*)}{A^*f(A)}\right)\right.\\&\left.+\left(\frac{f(A)}{f(A^*)}-\frac{A}{A^*}\right)\left(1-\frac{f(A^*)}{f(A)}\right)\right]+\sigma\beta E^*f(A^*)\left[-g\left(\frac{S^*}{S}\right)-g\left(\frac{SE^*}{S^*E}\right)-g\left(\frac{Ef(A)A^*}{E^*f(A^*)A}\right)-g\left(\frac{Af(A^*)}{A^*f(A)}\right)\right.\\&\left.+\left(\frac{f(A)}{f(A^*)}-\frac{A}{A^*}\right)\left(1-\frac{f(A^*)}{f(A)}\right)\right],\end{aligned} \tag{18}$$

where $g(x) = x - 1 - \ln x \geq 0$ for all $x > 0$. Furthermore, the assumption of $f(A)$ implies that

$$\left(\frac{f(A)}{f(A^*)} - \frac{A}{A^*}\right)\left(1 - \frac{f(A^*)}{f(A)}\right) \leq 0, \tag{19}$$

which leads to $L'_{P^*} \leq 0$ and the largest compact invariant set of $L'_{P^*} \leq 0$ is the singleton $\{P^*\}$. Therefore, by LaSalle's invariance principle, P^* is globally asymptotically stable when $\mathscr{R}_0 > 1$. □

3. Discrete Drinking Model

3.1. Model Formulation. By applying the Mickens nonstandard finite difference scheme, we discretize the continuous model (1) and construct the following discrete system:

$$\begin{cases} \dfrac{S_{n+1} - S_n}{h} = (1-q)\Lambda - \beta S_{n+1} f(A_n) - (\mu_S + p) S_{n+1}, \\[2ex] \dfrac{E_{n+1} - E_n}{h} = p S_{n+1} - \sigma\beta E_{n+1} f(A_n) - (\mu_E + \varepsilon) E_{n+1}, \\[2ex] \dfrac{A_{n+1} - A_n}{h} = (S_{n+1} + \sigma E_{n+1})\beta f(A_n) - (\mu_A + \gamma) A_{n+1}, \\[2ex] \dfrac{R_{n+1} - R_n}{h} = q\Lambda + \gamma A_{n+1} + \varepsilon E_{n+1} - \mu_R R_{n+1}, \end{cases} \tag{20}$$

where $n \in \mathscr{N}$, $h > 0$, denoting the time step size. S_n, E_n, A_n, and R_n are the approximations of variables $S(t)$, $E(t)$, $A(t)$, and $R(t)$ in (1) at the discrete time $t = nh$, respectively, and the parameters in (20) are the same as in (1).

Similar to system (1), the solution of (20) with nonnegative initial values is nonnegative and exists for all $t \geq 0$, and it is suffice to consider the following reduced system in Ω:

$$\begin{cases} \dfrac{S_{n+1} - S_n}{h} = (1-q)\Lambda - \beta S_{n+1} f(A_n) - (\mu_S + p) S_{n+1}, \\[2ex] \dfrac{E_{n+1} - E_n}{h} = p S_{n+1} - \sigma\beta E_{n+1} f(A_n) - (\mu_E + \varepsilon) E_{n+1}, \\[2ex] \dfrac{A_{n+1} - A_n}{h} = (S_{n+1} + \sigma E_{n+1})\beta f(A_n) - (\mu_A + \gamma) A_{n+1}. \end{cases} \tag{21}$$

Furthermore, it is easy to show that system (20) may have exactly the same equilibria as P_0 and P^* in the corresponding continuous system (1). The positive alcohol-present equilibrium P^* exists for all $\mathscr{R}_0 > 1$ with the alcoholics determined by the following equation:

$$\frac{1}{\beta f(A^*) + \mu_S + p} + \frac{\sigma p}{(\beta f(A^*) + \mu_S + p)(\sigma\beta f(A^*) + \mu_E + \varepsilon)} = \frac{(\mu_A + \gamma) A^*}{(1-q)\Lambda\beta f(A^*)}, \tag{22}$$

where $\mathscr{R}_0$ is the basic reproductive number defined in (6).

3.2. Stability Analysis. Since the discretization of the continuous model generally performs as a method of approximation for the analytic solution, it is supposed for the discrete model to preserve the dynamical properties of the corresponding continuous model as much as possible. In the following, we will conduct the global stability of the equilibria of system (20) to examine its consistency and efficiency.

Theorem 3. *For any time step $h > 0$, the alcohol-free equilibrium P_0 of system (20) is globally asymptotically stable when $\mathscr{R}_0 < 1$.*

Proof. To use the Jury criterion, we rearrange the discrete system (20) and get the Jacobian matrix at P_0 as

$$\begin{pmatrix} \dfrac{1}{1 + h(\mu_S + p)} & 0 & -\dfrac{S_0 h\beta f'(0)}{1 + h(\mu_S + p)} \\[2ex] \dfrac{hp}{1 + h(\mu_E + \varepsilon)} & \dfrac{1}{1 + h(\mu_E + \varepsilon)} & -\dfrac{E_0 h\sigma\beta f'(0)}{1 + h(\mu_E + \varepsilon)} \\[2ex] 0 & 0 & \dfrac{1 + h(S_0 + \sigma E_0)\beta f'(0)}{1 + h(\mu_A + \gamma)} \end{pmatrix}, \tag{23}$$

noting that

$$\begin{aligned} S_0 + h(1-q)\Lambda &= S_0(1 + h(\mu_S + p)), \\ E_0 + hpS_0 &= E_0(1 + h(\mu_E + \varepsilon)). \end{aligned} \tag{24}$$

Therefore, the characteristic equation has eigenvalues:

$$\begin{aligned} \lambda_1 &= \frac{1}{1 + h(\mu_S + p)}, \\ \lambda_2 &= \frac{1}{1 + h(\mu_E + \varepsilon)}, \\ \lambda_3 &= \frac{1 + h(S_0 + \sigma E_0)\beta f'(0)}{1 + h(\mu_A + \gamma)}, \end{aligned} \tag{25}$$

with $\lambda_i < 1\,(i = 1, 2, 3)$ for any $h > 0$ due to the fact $(S_0 + \sigma E_0)\beta f'(0) < \mu_A + \gamma$, which implies that P_0 is locally stable.

Then, define the following Lyapunov function:

$$L_n = c\left\{S_n - S_0 - S_0 \ln \frac{S_n}{S_0} + E_n - E_0 - E_0 \ln \frac{E_n}{E_0} + [1 + h(\mu_A + \gamma)]A_n\right\}, \tag{26}$$

where $c = 1/(\mu_A + \gamma)$. Noticing that the inequality $\ln x \le x - 1$ is valid for any $x > 0$, then we have

$$\begin{aligned} L_{n+1} - L_n &= c\left\{S_{n+1} - S_n + S_0 \ln \frac{S_n}{S_{n+1}} + [1 + h(\mu_A + \gamma)](A_{n+1} - A_n) + E_{n+1} - E_n + E_0 \ln \frac{E_n}{E_{n+1}}\right\} \\ &\le c\left\{\left(1 - \frac{S_0}{S_{n+1}}\right)(S_{n+1} - S_n) + [1 + h(\mu_A + \gamma)](A_{n+1} - A_n) + \left(1 - \frac{E_0}{E_{n+1}}\right)(E_{n+1} - E_n)\right\} \\ &= hc\left\{\left(1 - \frac{S_0}{S_{n+1}}\right)((1-q)\Lambda - \beta S_{n+1} f(A_n) - (\mu_S + p)S_{n+1}) + \left(1 - \frac{E_0}{E_{n+1}}\right)(pS_{n+1} - \sigma\beta E_{n+1} f(A_n) - (\mu_E + \varepsilon)E_{n+1})\right\} \\ &\quad + hc([S_{n+1} + \sigma E_{n+1}]\beta f(A_n) - (\mu_A + \gamma)A_n). \end{aligned} \tag{27}$$

In view of the equalities $(1-q)\Lambda = (\mu_S + p)S_0$ and $pS_0 = (\mu_E + \varepsilon)E_0$, we obtain

$$\begin{aligned} L_{n+1} - L_n &\le hc\left\{(\mu_S + p)S_0\left(2 - \frac{S_0}{S_{n+1}} - \frac{S_{n+1}}{S_0}\right) + (\mu_E + \varepsilon)E_0\left(2 - \frac{E_0}{E_{n+1}} - \frac{E_{n+1}}{E_0}\right) + \beta S_0 f(A_n) + \sigma\beta E_0 f(A_n) - (\mu_A + \gamma)A_n \right. \\ &\quad \left. + pS_0\left(\frac{S_{n+1}}{S_0} - 1 - \frac{E_0 S_{n+1}}{E_{n+1} S_0} + \frac{E_0}{E_{n+1}}\right)\right\} \\ &= hc\left\{\mu_S S_0\left(2 - \frac{S_0}{S_{n+1}} - \frac{S_{n+1}}{S_0}\right) + (\mu_E + \varepsilon)E_0\left(3 - \frac{S_0}{S_{n+1}} - \frac{E_{n+1}}{E_0} - \frac{S_{n+1}E_0}{S_0 E_{n+1}}\right) + \beta S_0 f(A_n) + \sigma\beta E_0 f(A_n) - (\mu_A + \gamma)A_n \right. \\ &\quad \left. + \beta S_{n+1} f(A_n)\left(1 - \frac{S_0}{S_{n+1}}\right)\right\} \\ &\le hc\left\{\mu_S S_0\left(2 - \frac{S_0}{S_{n+1}} - \frac{S_{n+1}}{S_0}\right) + (\mu_E + \varepsilon)E_0\left(3 - \frac{S_0}{S_{n+1}} - \frac{E_{n+1}}{E_0} - \frac{S_{n+1}E_0}{S_0 E_{n+1}}\right)\right\} + hc[\beta S_0 f'(0)A_n + \sigma\beta E_0 f'(0)A_n - (\mu_A + \gamma)A_n] \\ &= hc\left\{\mu_S S_0\left(2 - \frac{S_0}{S_{n+1}} - \frac{S_{n+1}}{S_0}\right) + (\mu_E + \varepsilon)E_0\left(3 - \frac{S_0}{S_{n+1}} - \frac{E_{n+1}}{E_0} - \frac{S_{n+1}E_0}{S_0 E_{n+1}}\right)\right\} + (\mathscr{R}_0 - 1)A_n. \end{aligned} \tag{28}$$

Therefore, $\mathscr{R}_0 < 1$ ensures that $L_{n+1} - L_n \le 0$, which implies that $\{L_n\}$ is a monotonic decreasing sequence. Thus, the limit of this nonnegative sequence exists and $\lim_{n\longrightarrow\infty}(L_{n+1} - L_n) = 0$, which is equivalent to

$$\begin{aligned} \lim_{n\longrightarrow\infty} S_n &= S_0, \\ \lim_{n\longrightarrow\infty} E_n &= E_0, \\ \lim_{n\longrightarrow\infty} A_n &= A_0, \end{aligned} \tag{29}$$

when $\mathscr{R}_0 < 1$. It is observed from (20) that $\lim_{n\longrightarrow\infty} A_n = 0$, then it yields that P_0 is globally asymptotically stable when $R_0 < 1$. □

Theorem 4. *For any time step $h > 0$, if $\mathscr{R}_0 > 1$, the unique alcohol-present equilibrium P^* is globally asymptotically stable.*

Proof. Define a Lyapunov function as

$$U_n = S_n - S^* - S^* \ln \frac{S_n}{S^*} + E_n - E^* - E^* \ln \frac{E_n}{E^*} + A_n - A^* - A^* \ln \frac{A_n}{A^*}, \tag{30}$$

and then the following holds:

$$\begin{aligned}
U_{n+1}-U_n &= S_{n+1}-S_n+S^*\ln\frac{S_n}{S_{n+1}}+E_{n+1}-E_n+E^*\ln\frac{E_n}{E_{n+1}}+A_{n+1}-A_n+A^*\ln\frac{A_n}{A_{n+1}}\\
&\le \left(1-\frac{S^*}{S_{n+1}}\right)(S_{n+1}-S_n)+\left(1-\frac{E^*}{E_{n+1}}\right)(E_{n+1}-E_n)+\left(1-\frac{A^*}{A_{n+1}}\right)(A_{n+1}-A_n)\\
&= h\left(1-\frac{S^*}{S_{n+1}}\right)[(1-q)\Lambda-\beta S_{n+1}f(A_n)-(\mu_S+p)S_{n+1}]+h\left(1-\frac{E^*}{E_{n+1}}\right)[pS_{n+1}-\sigma\beta E_{n+1}f(A_n)-(\mu_E+\varepsilon)E_{n+1}]\\
&\quad+h\left(1-\frac{A^*}{A_{n+1}}\right)[(S_{n+1}+\sigma E_{n+1})\beta f(A_n)-(\mu_A+\gamma)A_{n+1}].
\end{aligned} \tag{31}$$

For convenience, let $g(x)=x-1-\ln x$, then $g(x)$ is nonnegative for all $x>0$, and it has the minimum value $g(x)=0$ only at $x=1$. Noting that

$$\begin{aligned}
(1-q)\Lambda &= \beta S^* f(A^*)+(\mu_S+p)S^*,\\
pS^* &= (\mu_E+\varepsilon)E^*+\sigma\beta E^* f(A^*),
\end{aligned} \tag{32}$$

then substituting them into the above relation of $U_{n+1}-U_n$ leads to

$$\begin{aligned}
U_{n+1}-U_n &\le \left\{(\mu_S+p)S^*\left(2-\frac{S^*}{S_{n+1}}-\frac{S_{n+1}}{S^*}\right)+\left(1-\frac{S^*}{S_{n+1}}\right)(\beta S^* f(A^*)+\beta S_{n+1}f(A_n))+(\mu_E+\varepsilon)E^*\left(2-\frac{E^*}{E_{n+1}}-\frac{E_{n+1}}{E^*}\right)\right.\\
&\quad+pS^*\left(\frac{S_{n+1}}{S^*}-1-\frac{E^*S_{n+1}}{E_{n+1}S^*}+\frac{E^*}{E_{n+1}}\right)+\left(1-\frac{E^*}{E_{n+1}}\right)(\sigma\beta E^* f(A^*)-\sigma\beta E_{n+1}f(A_n))+\left(1-\frac{A^*}{A_{n+1}}\right)\\
&\quad\left.\cdot\left\{\beta S_{n+1}f(A_n)+\sigma\beta E_{n+1}f(A_n)-[\beta S^* f(A^*)+\sigma\beta E^* f(A^*)]\frac{A_{n+1}}{A^*}\right\}\right\}\\
&= h\left\{\mu_S S^*\left(2-\frac{S^*}{S_{n+1}}-\frac{S_{n+1}}{S^*}\right)+(\mu_E+\varepsilon)E^*\left(3-\frac{S^*}{S_{n+1}}-\frac{E_{n+1}}{E^*}-\frac{S_{n+1}E^*}{S^*E_{n+1}}\right)+\beta S^* f(A^*)\right.\\
&\quad\cdot\left[-g\left(\frac{S^*}{S_{n+1}}\right)-g\left(\frac{S_{n+1}f(A_n)A^*}{S^*f(A^*)A_{n+1}}\right)+\frac{f(A_n)}{f(A^*)}-\frac{A_n}{A^*}\right]+\sigma\beta E^* f(A^*)\\
&\quad\left.\cdot\left[-g\left(\frac{S^*}{S_{n+1}}\right)-g\left(\frac{S_{n+1}E^*}{S^*E_{n+1}}\right)-g\left(\frac{E_{n+1}f(A_n)A^*}{E^*f(A^*)A_n}\right)+\frac{f(A_n)}{f(A^*)}-\frac{A_n}{A^*}\right]\right\}\\
&= h\left\{\mu_S S^*\left(2-\frac{S^*}{S_{n+1}}-\frac{S_{n+1}}{S^*}\right)+(\mu_E+\varepsilon)E^*\left(3-\frac{S^*}{S_{n+1}}-\frac{E_{n+1}}{E^*}-\frac{S_{n+1}E^*}{S^*E_{n+1}}\right)+\beta S^* f(A^*)\right.\\
&\quad\cdot\left[-g\left(\frac{S^*}{S_{n+1}}\right)-g\left(\frac{S_{n+1}f(A_n)A^*}{S^*f(A^*)A_{n+1}}\right)-g\left(\frac{A_{n+1}f(A^*)}{A^*f(A_n)}\right)+\left(\frac{f(A_n)}{f(A^*)}-\frac{A_{n+1}}{A^*}\right)\left(1-\frac{f(A^*)}{f(A_n)}\right)\right]+\sigma\beta E^* f(A^*)\\
&\quad\left.\cdot\left[-g\left(\frac{S^*}{S_{n+1}}\right)-g\left(\frac{S_{n+1}E^*}{S^*E_{n+1}}\right)-g\left(\frac{E_{n+1}f(A_n)A^*}{E^*f(A^*)A_{n+1}}\right)-g\left(\frac{A_{n+1}f(A^*)}{A^*f(A_n)}\right)+\left(\frac{f(A_n)}{f(A^*)}-\frac{A_n}{A^*}\right)\left(1-\frac{f(A^*)}{f(A_n)}\right)\right]\right\}.
\end{aligned} \tag{33}$$

From the assumption of $f(A)$, we obtain that $(f(A_n)/f(A^*))-(A_n/A^*)\ge 0$ for $A_n\le A^*$ or, conversely, $(f(A_n)/f(A^*))-(A_n/A^*)\le 0$ for $A_n\ge A^*$, which gives

$$\left(\frac{f(A_n)}{f(A^*)}-\frac{A_n}{A^*}\right)\left(1-\frac{f(A^*)}{f(A_n)}\right)\le 0, \tag{34}$$

and the equality holds only if $A_n=A^*$. For all $S,E>0$, it is easy to verify that

$$\begin{aligned}
2-\frac{S^*}{S_{n+1}}-\frac{S_{n+1}}{S^*} &\le 0,\\
3-\frac{S^*}{S_{n+1}}-\frac{E_{n+1}}{E^*}-\frac{S_{n+1}E^*}{S^*E_{n+1}} &\le 0,
\end{aligned} \tag{35}$$

and the equalities are valid only for $S_n=S^*$ and $E_n=E^*$. Therefore, from the above deduction, we have $U_{n+1}-U_n\le 0$

and $U_{n+1} - U_n = 0$ if and only if $S_n = S^*$, $E_n = E^*$, and $A_n = A^*$. As a result, P^* is globally asymptotically stable when $\mathscr{R}_0 > 1$.

From the theoretical results in this section, it can be seen that the basic reproductive number is a crucial threshold which determines the dynamics of the model. From epidemiological viewpoint, alcohol abuse will eventually die out when $\mathscr{R}_0 < 1$. Otherwise, it will persist at the alcohol-present equilibrium when $\mathscr{R}_0 > 1$. □

4. Numerical Simulations

In this section, numerical simulations of model (1) and model (20) are provided to illustrate the theoretical results, including the global stabilities of the equilibria when the basic reproductive number $\mathscr{R}_0 < 1$ and $\mathscr{R}_0 > 1$, respectively, with the aim to demonstrate the consistency and efficiency of the discrete model in preserving the dynamic behaviors of the corresponding continuous model. In addition, the influence of some parameters on the basic reproductive number is examined, such as p, σ, and ε, which are related with the public health education. In models (1) and (20), the incidence rate is taken as the general form. In the following, we conduct numerical simulations by choosing two specific types of incidence, i.e., $f(A) = A$ and $f(A) = A/(1 + \alpha A)$.

4.1. Stability Preserving

(i) Case 1: $f(A) = A$.

In this case, the parameters are chosen as $\Lambda = 3.469$, $q = 0.75$, $\mu_S = 0.25$, $p = 0.9$, $\mu_E = 0.25$, $\mu_A = 0.3$, $\varepsilon = 0.2$, $\mu_R = 0.25$, $\gamma = 0.2$, $\beta = 0.3$, and $\sigma = 0.2$. With these parameters, the basic reproductive number is computed as $\mathscr{R}_0 = 0.6335 < 1$. Figure 1(a) shows that the alcohol-free equilibrium $P_0 = (0.7542, 1.5082, 0, 11.6136)$ is globally asymptotically stable (variable $R(t)$ is omitted for clarity in plots). When p and ε are reduced to $p = 0.265$ and $\varepsilon = 0.1$, and the other parameters remain the same, we have $\mathscr{R}_0 = 1.1634 > 1$, which leads to the global stability of $P^* = (1.4560, 1.0536, 0.2689, 11.0437)$, as plotted in Figure 1(b).

For comparison, we conduct simulations for the discrete model (20) with $f(A) = A$. The parameters are taken the same as in Figure 1. Firstly, we have $\mathscr{R}_0 = 0.6335 < 1$, corresponding to the case in Figure 1(a). Let the time step be $h = 0.4, 2, 5, 10$, respectively. As shown in Figure 2, the alcohol-free equilibrium P_0 is globally asymptotically stable, which is consistent with Theorem 3. To illustrate the dynamical behaviors of model (20) when $\mathscr{R}_0$ being greater than 1, we compare it with Figure 1(b), i.e., $\mathscr{R}_0 = 1.1634 > 1$. Figure 3 shows that the alcohol-present equilibrium P^* is globally stable, which is consistent with Theorem 4. From Figures 2 and 3, we can see that the discrete model (20) preserves exactly the dynamical properties of the corresponding continuous model (1), and the increasing time step size from $h = 0.4$ to $h = 10$ has no effect on the stability of the equilibria, indicating the efficiency and consistency of the proposed method for discretization.

(ii) Case 2: $f(A) = A/(1 + \alpha A)$.

When the general incidence function is specified as this type of saturated form, numerical solutions of model (1) and model (20) are simulated when the basic reproductive number is less or greater than 1, respectively. If the parameters are chosen as $\Lambda = 3.8$, $q = 0.75$, $\mu_S = 0.25$, $p = 0.85$, $\mu_E = 0.25$, $\mu_A = 0.28$, $\varepsilon = 0.15$, $\mu_R = 0.25$, $\gamma = 0.26$, $\beta = 0.3$, $\sigma = 0.22$, and $\alpha = 0.5$, then for this set of parameter values, $\mathscr{R}_0 = 0.7041 < 1$ and the alcohol-free equilibrium $P_0 = (0.8637, 1.8352, 0, 12.5012)$ is globally asymptotically stable, as shown in Figure 4(a). If p is reduced from 0.85 to 0.24 and the other parameters remain the same,then $\mathscr{R}_0 = 1.2193 > 1$, and all the solutions of model (1) converge to the alcohol-present equilibrium $P^* = (1.7498, 1.0201, 0.1935, 12.2133)$, as plotted in Figure 4(b).

For the corresponding discrete model (20), the numerical simulations are also conducted to check its stability preserving in this case. All the parameter values are taken the same as in Figure 4 and set the time step size h as 0.4, 2, 5, and 10, respectively. With these parameters, we have $\mathscr{R}_0 = 0.7041 < 1$, corresponding to Figure 4(a). As desired, the alcohol-free equilibrium P_0 is asymptotically stable, as shown in Figure 5. When $\mathscr{R}_0 = 1.2193 > 1$, the simulation result is presented in Figure 6, which is corresponding to Figure 4(b). From the plot, we can see that the numerical solutions of model (20) converge to P^*, showing the expected consistency of the obtained discrete model (20) with the original continuous model (1). Furthermore, it is depicted in Figures 5 and 6 that the dynamical properties will not be influenced by increasing the time step size; i.e., whether alcohol abuse persists or not is completely determined by the basic reproductive number, no matter what the time step is taken.

Remark. When the general incidence in models (1) and (20) is taken as other forms, such as Beddington–DeAngelis response ($\beta SA/(1 + aS + bA)$) and Crowley–Martin response ($\beta SA/(1 + aS + bA + abSA)$), numerical simulations about stability preserving present the similar results as in Figures 1–6.

4.2. Effect of Public Health Education. In the modelling, we introduce two different susceptibilities due to consideration of public health education, which is perceived as an effective strategy to reduce alcohol abuse. When people are influenced by these educational campaigns, some of them may consequently have a relatively low probability of being affected by alcoholics as well as a high rate of moving to the nondrinker class. In the following, the parameters that reflect the effort of public health education are highlighted, i.e., p (rate moving from the susceptible to the educated class), σ (reduced infectiousness of educated individuals relative to susceptible ones), and ε (rate moving from the educated class to the no-drinker class).

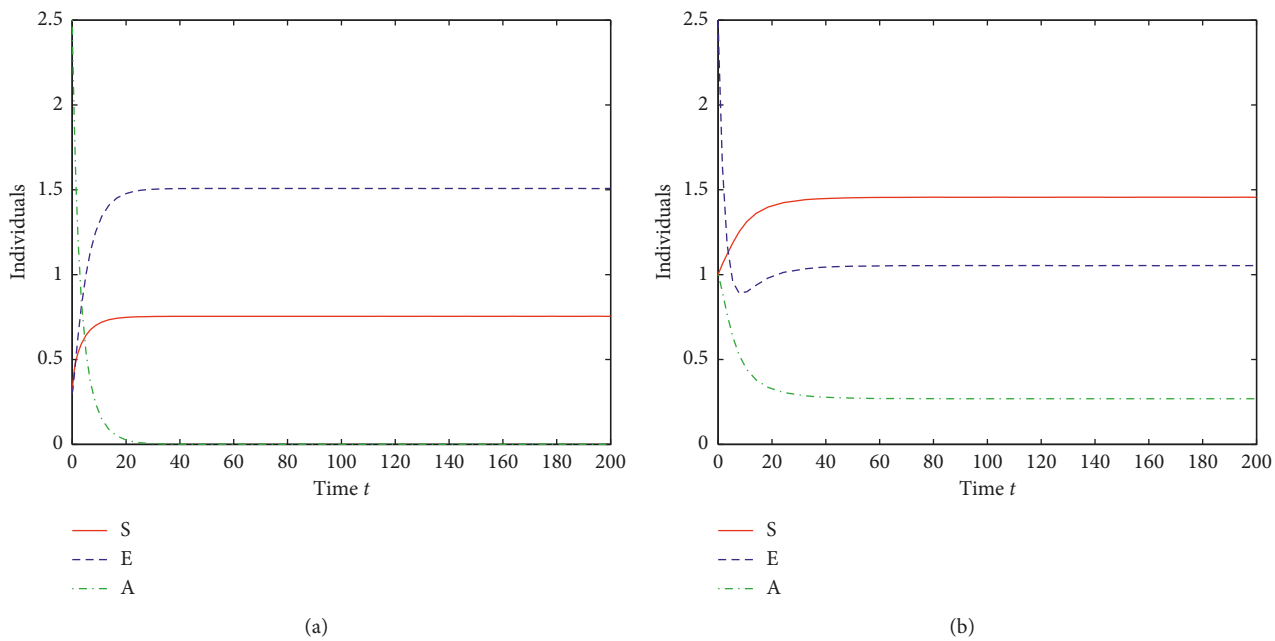

Figure 1: Global stabilities of the equilibria P_0 and P^* for model (1) with $f(A) = A$. (a) P_0 is globally asymptotically stable when $\mathscr{R}_0 = 0.6335 < 1$. (b) P^* is globally asymptotically stable when $\mathscr{R}_0 = 1.1634 > 1$.

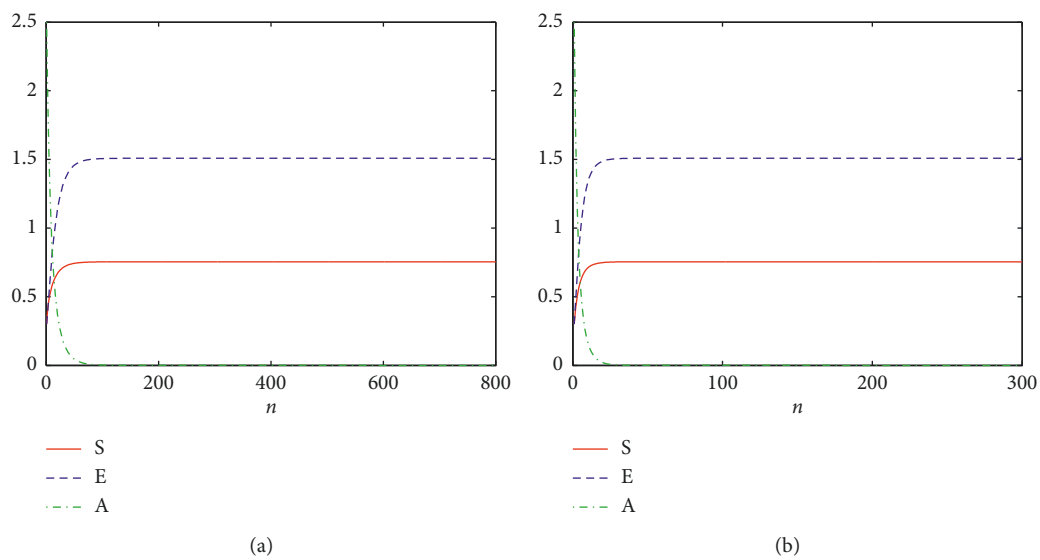

Figure 2: Continued.

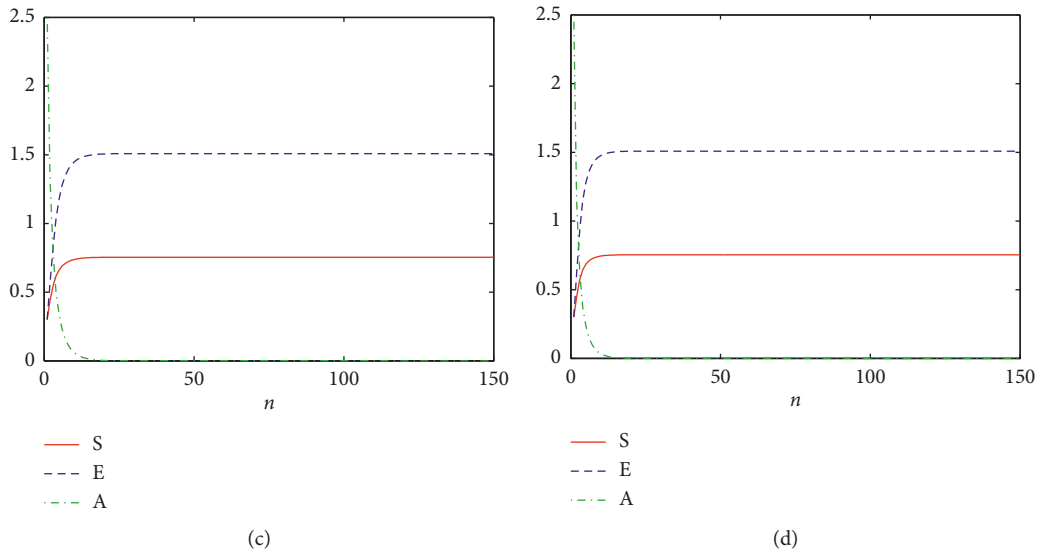

Figure 2: Global stability of P_0 for model (20) with $f(A) = A$ when $\mathscr{R}_0 = 0.6335 < 1$: (a) $h = 0.4$; (b) $h = 2$; (c) $h = 5$; (d) $h = 10$.

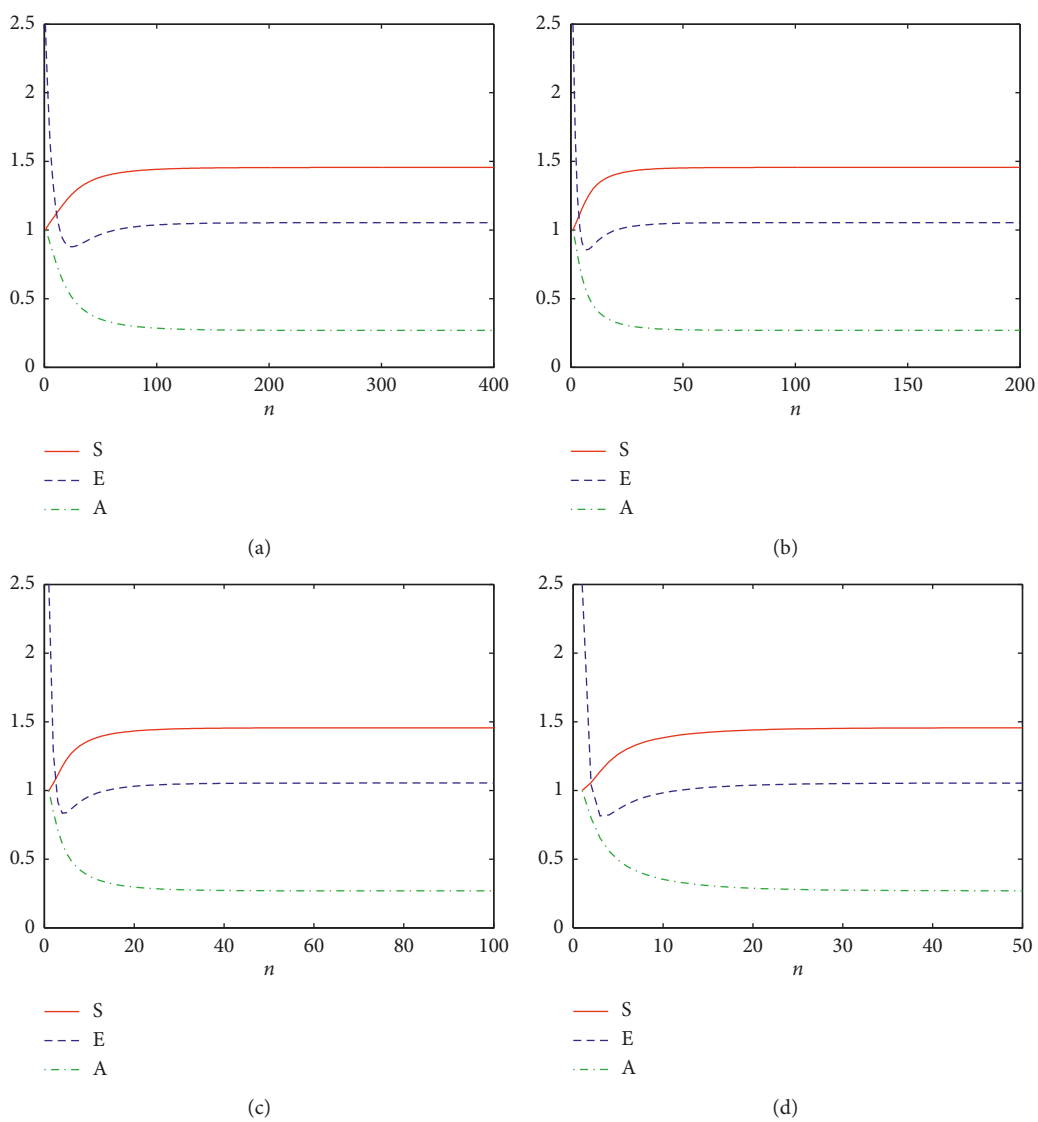

Figure 3: Global stability of P^* for model (20) with $f(A) = A$ when $\mathscr{R}_0 = 1.1634 > 1$: (a) $h = 0.4$; (b) $h = 2$; (c) $h = 5$; (d) $h = 10$.

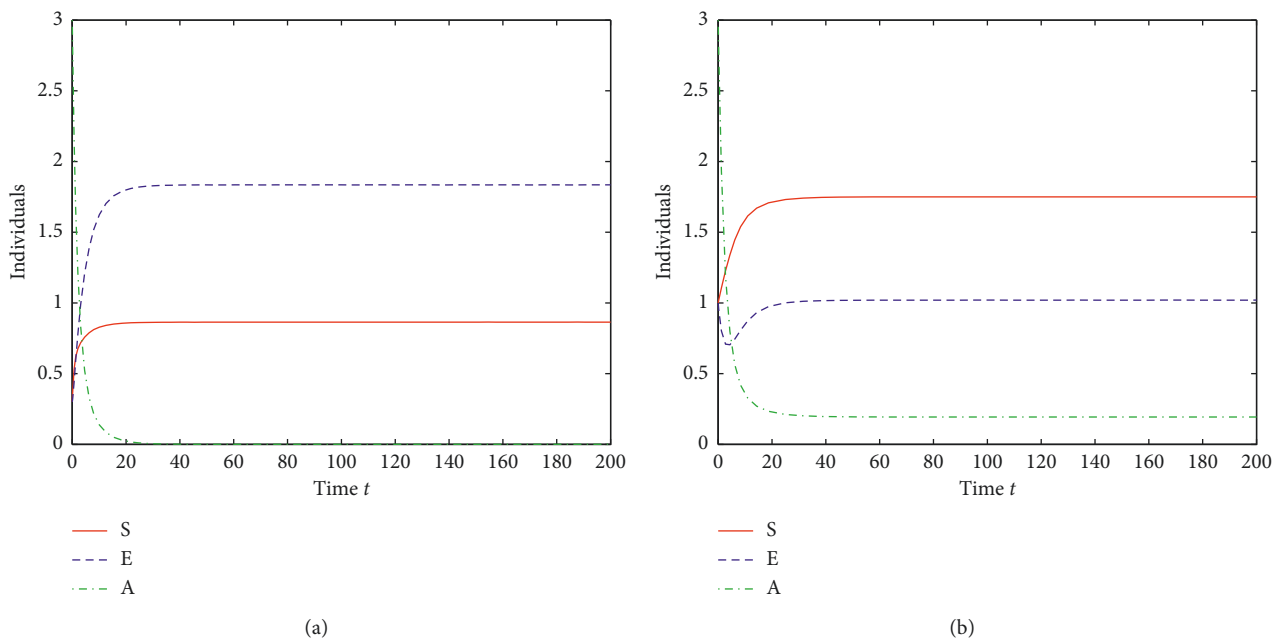

Figure 4: Global stabilities of the equilibria P_0 and P^* for model (1) with $f(A) = A/(1 + \alpha A)$. (a) P_0 is globally asymptotically stable when $\mathscr{R}_0 = 0.7041 < 1$. (b) P^* is globally asymptotically stable when $\mathscr{R}_0 = 1.2193 > 1$.

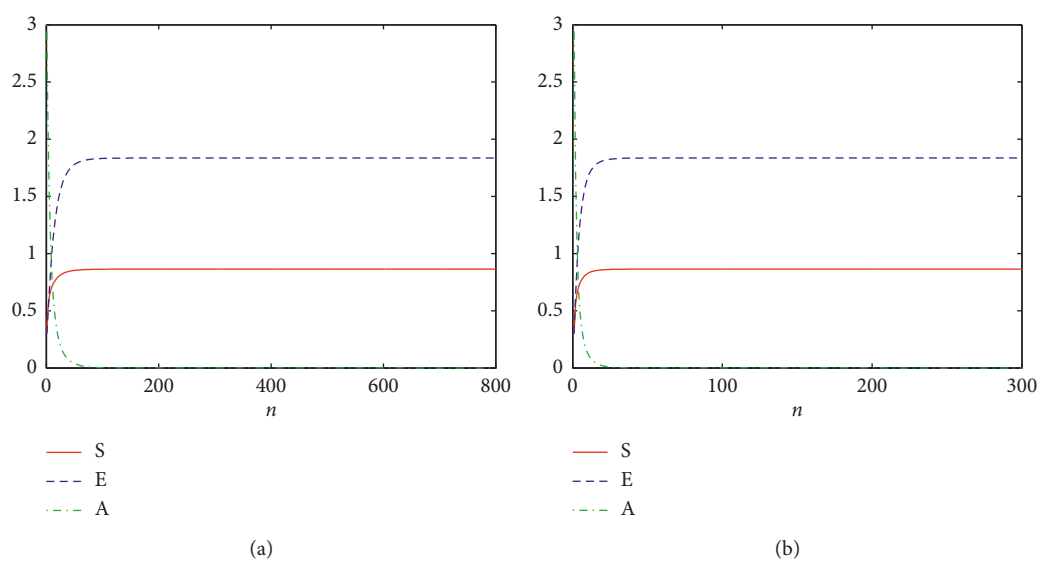

Figure 5: Continued.

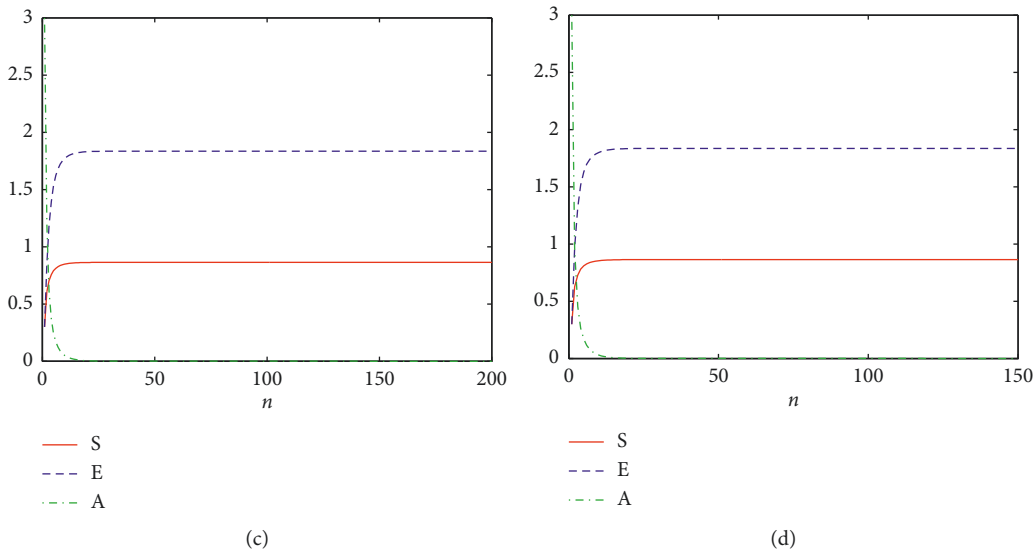

Figure 5: Global stability of P_0 for model (20) with $f(A) = A/(1+\alpha A)$ when $\mathscr{R}_0 = 0.7041 < 1$: (a) $h = 0.4$; (b) $h = 2$; (c) $h = 5$; (d) $h = 10$.

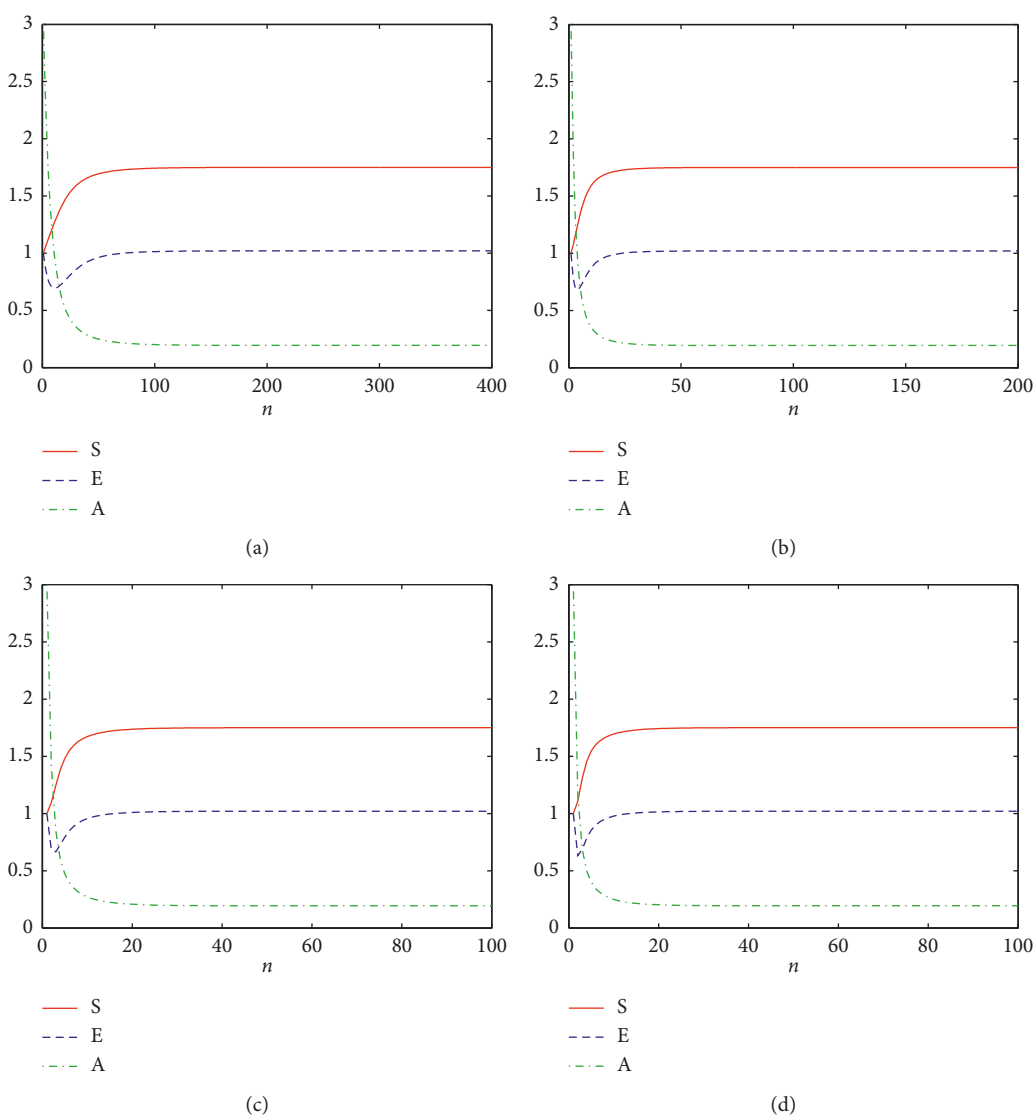

Figure 6: Global stability of P^* for model (20) with $f(A) = A/(1+\alpha A)$ when $\mathscr{R}_0 = 1.2193 < 1$: (a) $h = 0.4$; (b) $h = 2$; (c) $h = 5$; (d) $h = 10$.

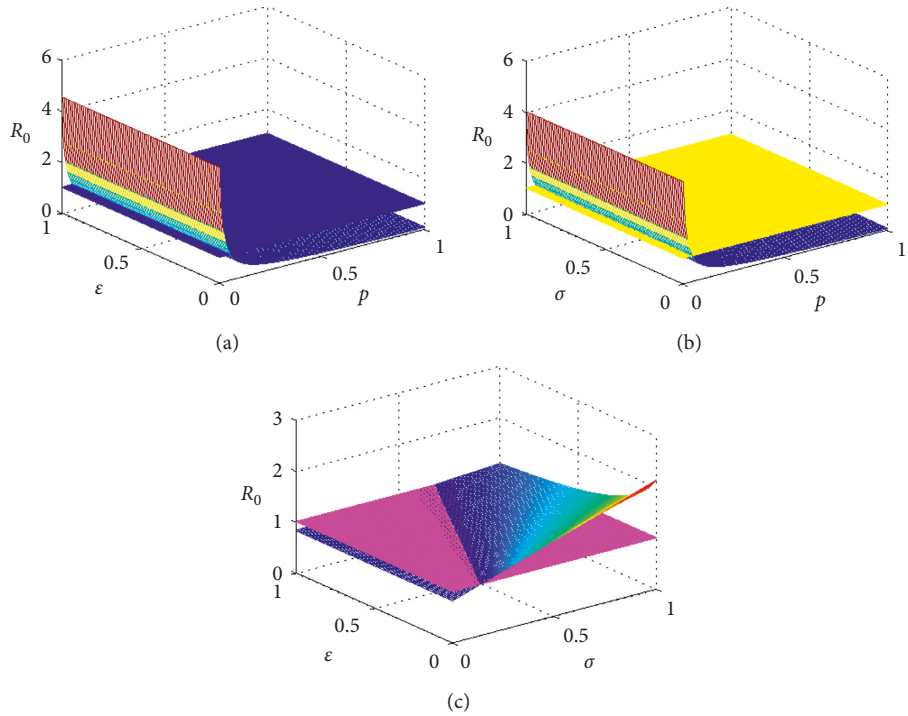

Figure 7: Dependence of $\mathscr{R}_0$ on the parameter pairs of (p, ε), (p, σ), and (σ, ε).

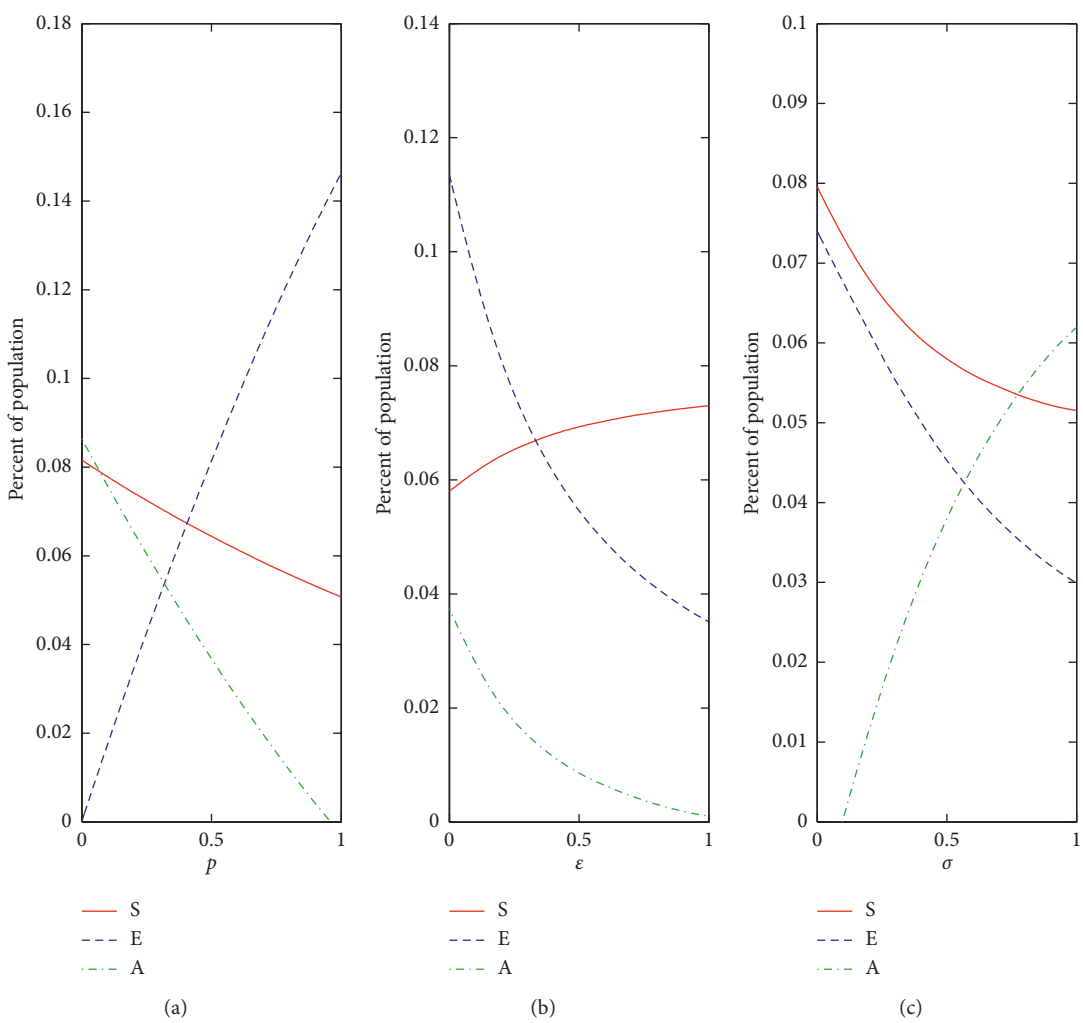

Figure 8: Percent of S, E, and A in the whole population with varying (a) p, (b) ε, and (c) σ, respectively.

To evaluate the educational campaign and demonstrate the impact of these parameters, we investigate the sensitivity of parameter variations on the basic reproductive number $\mathscr{R}_0$, which plays an important role in determining the dynamics of the model. By (6), we can get the derivatives of $\mathscr{R}_0$ about p, σ, and ε, respectively, as follows:

$$\begin{aligned}
\frac{\partial \mathscr{R}_0}{\partial p} &= \frac{\beta f'(0)(1-q)\Lambda(\sigma\mu_S - \mu_E - \varepsilon)}{(\mu_A+\gamma)(\mu_E+\varepsilon)(\mu_S+p)^2},\\
\frac{\partial \mathscr{R}_0}{\partial \varepsilon} &= -\frac{\beta f'(0)(1-q)\Lambda\sigma p}{(\mu_A+\gamma)(\mu_E+\varepsilon)^2(\mu_S+p)} < 0,\\
\frac{\partial \mathscr{R}_0}{\partial \sigma} &= \frac{\beta f'(0)(1-q)\Lambda p}{(\mu_A+\gamma)(\mu_E+\varepsilon)(\mu_S+p)} > 0.
\end{aligned} \tag{36}$$

For the derivative about p, it is negative if only $\sigma\mu_S - \mu_E - \varepsilon < 0$. In fact, noting that μ_S and μ_E are the death rates in the susceptible and the educated class, the difference between them is typically small enough in most actual situations, implying that $\partial\mathscr{R}_0/\partial p < 0$ can generally hold for all positive parameter values. Therefore, $\mathscr{R}_0$ is negatively related to p and ε but positively related to σ, revealing that the more effectively the public health education performs, the better results the alcoholic consumption control will produce.

The plots in Figure 7 illustrate the dependence of $\mathscr{R}_0$ on the parameter pairs of (p, ε), (p, σ), and (σ, ε), using the function of $f(A) = A$. The intersecting curves of $\mathscr{R}_0 = 1$ by the two surfaces $\mathscr{R}_0$ and the constant 1 reveal the parameter ranges in which the basic reproductive number is less than 1 and then the alcohol abuse can be controlled eventually. In Figure 8, the percent of S, E, and A in the whole population is presented when the three focused parameters p, ε, and σ vary from 0 to 1. As depicted in Figure 8, the percent of alcoholics can be held to a very low level (probably even to zero) as the effect of educational campaign rises, reflected by the increasing p and ε. However, it is also shown by the percent-σ plot that the lowered education strength allows for an obvious increase in the percent of alcoholics, which is induced by the waning knowledge of alcoholism in the public.

5. Conclusions

In this paper, we investigated the threshold dynamics of an SEAR alcoholism model with the form of continuous equations and discrete equations, noting that the discrete model is formulated by applying the Michens nonstandard finite difference scheme to the corresponding continuous model. With this method of discretization, as demonstrated by the theoretical and numerical results obtained in this paper, the dynamical properties of the continuous system can be preserved with much high efficiency when compared with the traditional schemes such as forward Euler and Runge–Kutta, which sometimes fail generating oscillations, bifurcations, and chaos, and even result in false steady states [35, 36]. Specifically, not only the expressions of equilibria and the basic reproductive number but also the threshold dynamics are identical in both models (1) and (20), which confirm its consistency of the discrete model with the original continuous model in the qualitative properties.

For some troubling contagions, such as alcohol drinking, improving public knowledge forms part of the perceived strategy to prevent the spread. Public health education, which may substantially contribute to an effective management of this health problem, is incorporated in our model by introducing two different susceptibilities. To analyze the impact of parameters related with public health education, numerical simulations are conducted to demonstrate the effect of them on the basic reproductive number and on the percentage of a different drinking status in whole population. The results show that educational campaign plays an important role in controlling alcoholism (seen in Figures 7 and 8), which can be held to a very low level (eventually dies out) when some parameters related with public health education remain in certain intervals. Meanwhile, educational campaign is also expected to perform efficiently in reducing the initiation and maintenance of alcohol consumption.

Data Availability

All the data used to support the findings of this study are included in our manuscript and can be accessed freely from the references.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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