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Comparative Study of the Malthusian Population Model and the Logistic Population Model for Bangladesh

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Abstract

Bangladesh has a denser population in comparison with many other countries. Though the rate of population increase has been regarded as a concerning issue, estimation of the population instability in the upcoming years may be useful for national planning. To predict Bangladesh's future population, this study compares the estimated populations of two popular population models, the Malthusian and the logistic population models, with the country's census population published by BBS. We also tried to find out which model gives a better approximation for forecasting the past, present, and future population between these two models.

Keywords

Malthusian Population Model, Logistic Population Model, Population Growth, Carrying Capacity

1. Introduction

Mathematical models are essential to identifying and predicting complex real-world occurrences because they provide a logical structure for evaluating and understanding dynamic systems. They enable the breakdown of complicated mechanisms into easily acquired components, enabling investigators to simulate and explore various scenarios. Through the use of mathematical models, we may better understand system behavior, predict outcomes based on data, and develop solutions for issues in a range of academic fields, such as biology and economics. In the study of population dynamics, the Malthusian and logistic population models have proven useful in constructing complicated patterns of population growth [1] [2]. The Malthusian model, developed in the 18th century by Thomas Robert

Malthus, assumes exponential population growth. This simple yet essential model serves as an outline for further research into how populations may increase swiftly when resources are sufficient. This model serves as a theoretical foundation, illustrating the unlimited optimism of unrestricted population growth [3]-[5]. On the other hand, carrying capacity a population growth limit established by environmental constraints is a component of the logistic population model. The nineteenth-century model developed by Pierre-François Verhulst incorporates a saturation effect to the Malthusian framework, acknowledging that circumstances and few resources prevent population growth from occurring continuously. It depicts population dynamics more realistically by accounting for the few resources and the external environment. The mathematical intricacies of these models will be thoroughly examined in this research, providing insight into their underlying presumptions, solutions, and outcomes. We get important insights into the mechanisms governing population increase by assessing both the logistic model's complicated equilibrium and the Malthusian model's inexhaustible optimism [6]-[9].

We intend to explore the mathematical formulations, assumptions, and consequences of these models as we begin this comparative query. We want to gain a better understanding of the fundamental mechanisms that influence population behavior by contrasting the Malthusian and Logistic perspectives. This investigation not only broadens our theoretical knowledge but also has practical implications for addressing concerns of sustainability and resource management in modern society.

2. Population Model

Population models serve as significant tools in many fields because they offer an angle through which one can study and predict population behavior in biological, ecological, and social settings. One popular model is the exponential growth model, which illustrates scenarios in which populations grow at a constant frequency. Bacteria, for example, generally display exponential growth in a controlled environment until limits to resources intrude [10] [11].

In ecology, the predator-prey model, as defined by the Lotka-Volterra equations, studies species interactions. This model presents an understanding of how predator and prey populations interact, exposing the delicate balance necessary for coexistence. Ecological models, such as compartmental models, provide data on disease transmission. These models classify individuals as Susceptible, Exposed, Infectious, and Recovered, which supports facilitating the creation of successful measures for public health [12].

Two important population models, the Logistic and Malthusian models, have played pivotal roles in developing our knowledge of population dynamics. The Logistic model, with its actual resource limits, and the Malthusian model, which depicts exponential development in the absence of constraints, provide different viewpoints on population dynamics [13]. We want to acquire significant insights into the past, present, and future trajectories of populations by unraveling the complexities of these mathematical frameworks, which will influence sectors ranging from ecology to economics.

2.1. Malthusian Population Model

Thomas Robert Malthus published his famous book "An Essay on the Principle of Population" in 1798. In the basic argument, Malthus suggests that there are diminishing returns to land, that is if we add more workers to the land, the land produces little amounts of additional value. This means that if the population doubles and we have twice the number of workers on the land, we don't produce double the amount of food. So, doubling the population means that each person actually has less food than that before. One of the earliest social theorists who connected the difference between modern Western cultures and non-Western and non-modern Western countries' opulence to human behavioral patterns was Thomas Malthus. His finding that inconsistent population growth contributes to modern fortune has had a significant impact on contemporary social theorists as well as Western social theorists. Malthus believed that family planning, as it is known now, needed the typical Western capacity to evaluate the advantages and disadvantages of having children and make informed decisions about whether to get married now or later [14]-[16]. Malthus gives the following population model:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = rN(t), \tag{1}$$

where r is the population growth rate which is a positive constant and also a constant of proportionality, and $N(t)$ is the number of individuals of the considered population at time t. The positive value of r indicates the population is increasing and the negative value of r indicates the population is decreasing. Since the solution of Equation (1) exponentially increases, the model can be called an unlimited population growth model. In real-world problems, population growth is restricted by food, space, and other necessities requirements for survival [17].

We will solve the Malthusian model that is Equation (1) by variable separation method of ODE as follows:

$$\begin{aligned}
&\frac{\mathrm{d}N(t)}{\mathrm{d}t} = rN(t) \\
&\Rightarrow \frac{\mathrm{d}N(t)}{N(t)} = r\mathrm{d}t \\
&\Rightarrow \int \frac{\mathrm{d}N(t)}{N(t)} = \int r\mathrm{d}t \\
&\Rightarrow \ln\left(N(t)\right) = rt + C_1 \\
&\Rightarrow \mathrm{e}^{\ln(N(t))} = \mathrm{e}^{rt+C_1} \\
&\Rightarrow N(t) = C\mathrm{e}^{rt},
\end{aligned} \tag{2}$$

where C is an integrating constant. Using initial condition, say at the starting time, that is when time $t = 0$, the initial population is $N(0) = N_0$. Putting $t = 0$ in the (2) equation we get

$$N(0) = Ce^0$$

$$\Rightarrow C = N_0$$

Then out Equation (2) becomes

$$\Rightarrow N(t) = N_0 e^{rt}$$

which is the solution of the Malthusian population model [18]-[20]. Solution curve is given below:

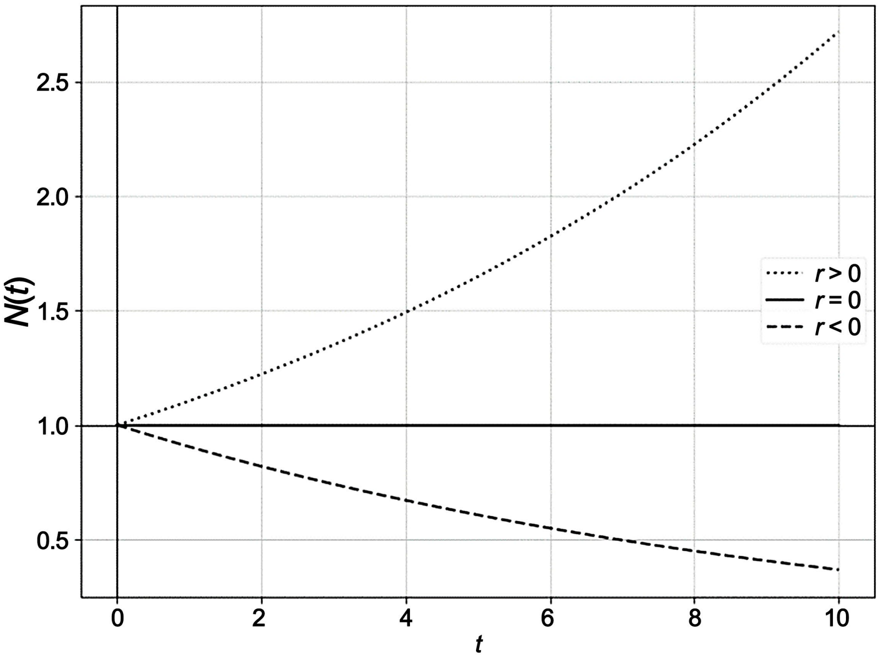


Figure 1. Malthusian population model's solution curve.

In **Figure 1**, we consider artificial values $N_0 = 1.0$ (initial value), and for positive growth rate $r = 0.1$ and $r = -0.1$ for negative growth rate in order to find a solution curve of the Malthusian population model. For negative growth rate population is decreasing, whereas for the positive growth rate population is increasing as time passes.

2.2. Logistic Population Model

A self-limiting component was added to logistic equations to represent population increase, acting as a withstand on the unbounded expansion of the Malthusian model b Belgian mathematician Pierre François Verhulst in 1838. It commonly used to forecast technological and economic progress as well as populations of humans, plants, animals, and microbes. The logistic equation is a non-linear equation of the form:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t}=rN(t)\left(1-\frac{N(t)}{K}\right),\ N(0)=N_0 \tag{3}$$

where r is the intrinsic growth rate, $N(t)$ denotes the population density at time t, K is the environmental carrying capacity and N_0 is the population density at time $t=0$.

The solution of the logistic Equation (3) is

$$N(t)=\frac{N_0K}{K\mathrm{e}^{-rt}+N_0\left(1-\mathrm{e}^{-rt}\right)} \tag{4}$$

where the carrying capacity, constant K is not realistic. Its value may vary if the environment changes. When the carrying capacity K and growth rate a is constant, we say Equation (3) is an autonomous system. For example, after the change of environment food availability can be changed. This change may create a positive or negative effect on the population of the species [21]-[23].

Instead of constant carrying capacity, time-dependent carrying capacity $K(t)$ is used in many studies for various applications. Using a time-varying transport capacity makes the logistic equation non-autonomous due to the explicit time dependence of $K(t)$. Then our above (3) logistic equation changed to

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t}=rN(t)\left(1-\frac{N(t)}{K(t)}\right), \tag{5}$$

where the carrying capacity

$$K(t)=K_s\left(1-\mathrm{e}^{-ct}\right)$$

Here K_s is the bacterial fertilization level, c is the fertilization constant, $b=\left(1-\frac{K_0}{K_s}\right)$, with $K(0)=K_0$ and $0<b<1$ [24]-[26].

Equation (3) is an ordinary differential Equation (ODE). To solve this equation, we will use the variable separation method. In this method, we first separate two variables on the right and left sides and then we integrate both sides. For finding the value of the integrating constant we will consider an initial guess.

The solution to Equation (3) is given below:

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t}=rN(t)\left(1-\frac{N(t)}{K}\right)$$

$$\Rightarrow\frac{\mathrm{d}N(t)}{N(t)\left(1-\frac{N(t)}{K}\right)}=r\mathrm{d}t$$

$$\Rightarrow\int\frac{\mathrm{d}N(t)}{N(t)\left(1-\frac{N(t)}{K}\right)}=\int r\mathrm{d}t$$

$$\Rightarrow\int\left(\frac{1}{N(t)}+\frac{1}{K-N(t)}\right)=\int r\mathrm{d}t$$

$$\Rightarrow \ln\left(N(t)\right)-\ln\left(K-N(t)\right)=rt+c$$

$$\Rightarrow \ln\left(\frac{\left(K-N(t)\right)}{N(t)}\right)=-rt-c$$

$$\Rightarrow \ln\left(\frac{\left(K-N(t)\right)}{N(t)}\right)=-rt-c$$

$$\Rightarrow \frac{K-N(t)}{N(t)}=A\mathrm{e}^{-rt}$$

$$\Rightarrow \frac{K}{N(t)}-1=A\mathrm{e}^{-rt}$$

$$\Rightarrow \frac{K}{N(t)}=1+A\mathrm{e}^{-rt}$$

$$\Rightarrow N(t)=\frac{K}{1+A\mathrm{e}^{-rt}} \tag{6}$$

Consider at the initial stage $t=0$, then density $N(0)=N_0$ and after replacing $N=N_0$ in (6) we get

$$A=\frac{K-N_0}{N_0}$$

Putting the value of A in Equation (6) we get the following equation

$$N(t)=\frac{K}{1+\frac{K-N_0}{N_0}\mathrm{e}^{-rt}}$$

$$N(t)=\frac{N_0K}{N_0+K\mathrm{e}^{-rt}-N_0\mathrm{e}^{-rt}}$$

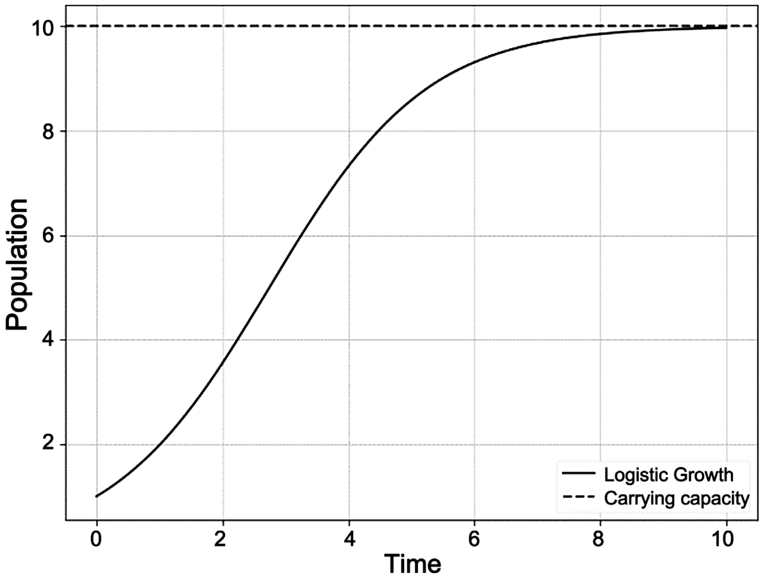


Figure 2. Logistic population model's solution curve.

$$N(t)=\frac{N_0K}{K\mathrm{e}^{-rt}+N_0\left(1-\mathrm{e}^{-rt}\right)} \tag{7}$$

Equation (7) is the solution of the autonomous logistic growth equation [27] [28]. Solution curve of logistic population model is represented bellow:

For **Figure 2**, we consider artificial values $K=10$ (Carrying capacity), initial population, $N_0=1$ at time $t=0$ and a growth rate of $r=0.8$. Clearly, after a certain time population doesn't increase realistically, as after that time the population becomes approximately equal to the carrying capacity, it tends to rise a little compared to the earlier time period.

3. Result and Discussions

In this section, first explains how the parameters for Malthusian population model and the classic logistic population model are calculated. Using following methods, we calculated the growth rate and carrying capacity for Bangladesh:

Growth Rate Calculation: We utilize the formula mentioned below to determine the growth rate of Bangladesh [29] [30].

$$r=-1+\left(\frac{\text{Present population}}{\text{starting Population}}\right)^{\frac{1}{\text{time period}}}$$

Therefore, population growth during this period is

$$r=-1+\left(\frac{171186372}{72947807}\right)^{\frac{1}{47}}=0.018315=1.8315\%$$

Carrying Capacity Calculation: To estimate the carrying capacity of Bangladesh using the formula [31],

$$\text{Carrying Capacity}=\frac{\text{Total Resources}}{\text{Resource Consumption per Person}}$$

For this calculation, we follow the following steps:

Food production: Bangladesh has a diverse agricultural sector. In recent years, annual rice production is around 35 million tons [32]. We can convert this to calories: 1 Kg of rice provides roughly 3500 calories. Therefore, 35 million tons of rice provide 35,000,000 tons × 1000 kg/ton × 3500 calories/kg = 122,500,000,000,000 calories. Also, for other food supplies including other staples and food sources like fish, vegetables, and pulses. Let's assume this adds 30.2 million tons, providing another 105,700,000,000,000 calories. Then the total food calories =
122,500,000,000,000 + 105,700,000,000,000 = 228,200,000,000,000 [33].

Water resources: Consider the annual renewable water resources. Bangladesh has about 1200 cubic kilometers of renewable freshwater. This becomes a significant factor if we estimate the per capita water need (drinking, sanitation, agriculture) to be around 2000 liters per person per day [34].

Resource consumption per person: The average caloric requirement for a person is about 2500 calories per day. Hence, the average caloric requirement for a person in a year is = 2500 × 365 = 912,500 calories/year [35] [36].

Calculation of carrying capacity: Using food as the primary resource for the calculation simplicity, we get

$$\text{Carrying Capacity} = \frac{228200000000000 \text{ calories}}{912500 \text{ calories perperson/year}} = 250082191 \approx 250 \text{ millions}$$

Calculation of this carrying capacity has some limiting factors, such as

- This calculation is based mainly on food production. Water availability, quality, and other factors (like land for habitation and infrastructure) are also critical.
- This estimate assumes current agricultural practices remain constant and do not degrade resources over time.
- Climate change, soil degradation, and pollution can significantly impact resource availability and consumption rates, which are ignored.

3.1. Current Population

In this section, we use the current population of Bangladesh to compare estimated population for the year 1974 to 2022 of both the Malthusian population model and the logistic population model (**Table 1**).

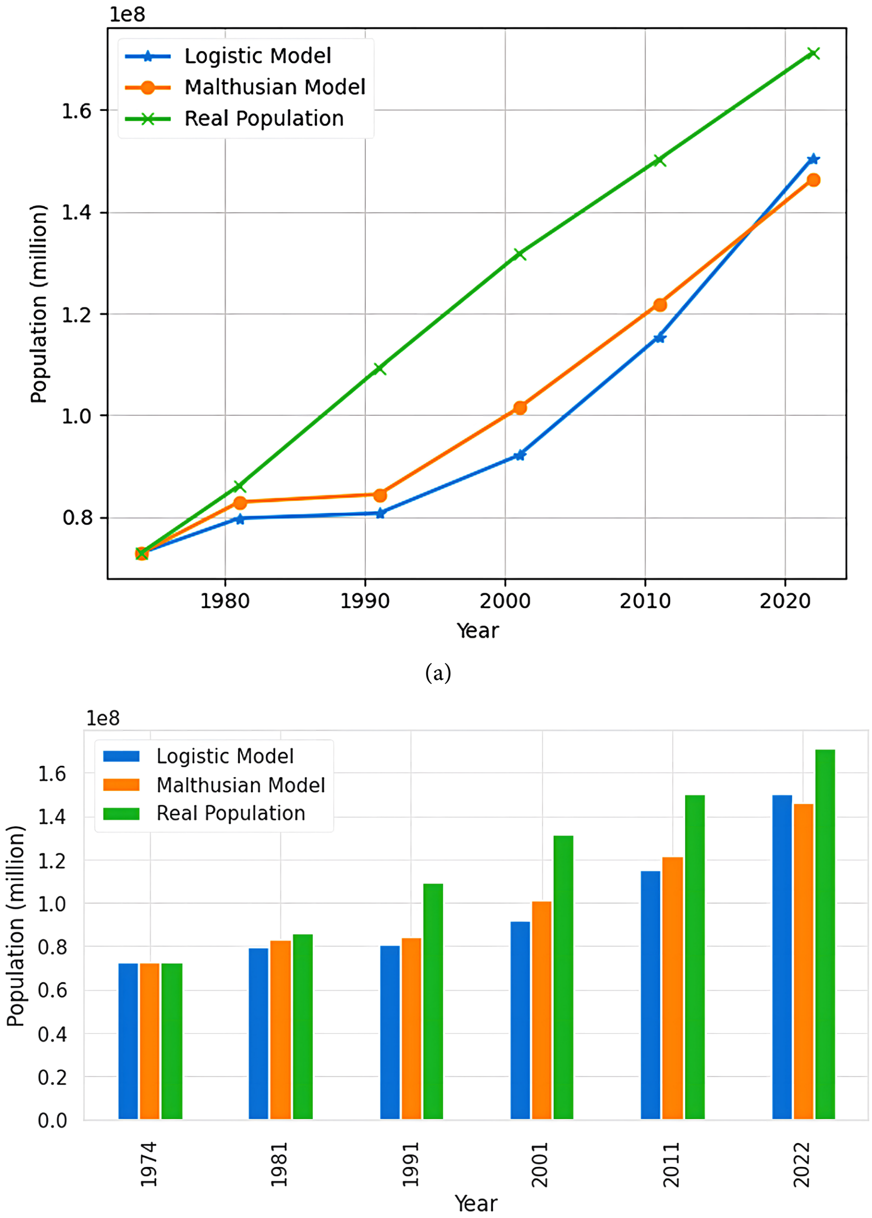
Table 1. Comparison between real population, and population according to the Malthusian population model and the logistic population model.

Year	Population from Census Data	Population Growth	Population According to Malthusian Population Model (Growth rate 1.8315%)	Population According to Logistic Population Model (Growth rate 1.8315%)
1974	72,947,807	2.53%	72,947,807	72,947,807
1981	86,154,836	2.65%	82,926,047	79,743,257
1991	109,242,834	1.96%	84,458,831	80,741,176
2001	131,670,484	1.92%	101,434,595	92,121,618
2011	150,211,005	1.23%	121,822,395	115,387,742
2022	171,186,372	1.08%	146,308,032	150,491,566

The population estimated from the Malthusian population model and the logistic population model are compared to the census population in this table. Here, we considered 1.8315% as the growth rate for both models and 250,000,000 as Bangladesh's highest possible capacity for the logistic population model. The inclusion of carrying capacity in the logistic population model has resulted in noticeable population variations between both models.

Figure 3 shows that the actual, Malthusian, and logistic population trajectories were initially at the point. However, over time, fluctuations between these three curves become visible, and we observe significant changes take place to the Malthusian and logistic model curves derived from census or real population curves.

The Malthusian curve was slightly above the logistic curve from 1974 to 1990; however, as time passed, an upsurge in the logistic population model's curve surpassed the Malthusian curve. The logistic curve moved above the Malthusian curve and began to approach the census's population curve between 2010 and 2020.



(a)

(b)

Figure 3. Comparison census population with the population from the Malthusian population model and the logistic population model.

As a result, the logistic population model's accuracy improves with time far more than the Malthusian population models. The Malthusian population curve continues to grow exponentially even when the logistic curve approaches the true population curve. This leads us to the conclusion that the Logistic population model produces more accurate results than the Malthusian population model for an actual population of a system over a long period of time.

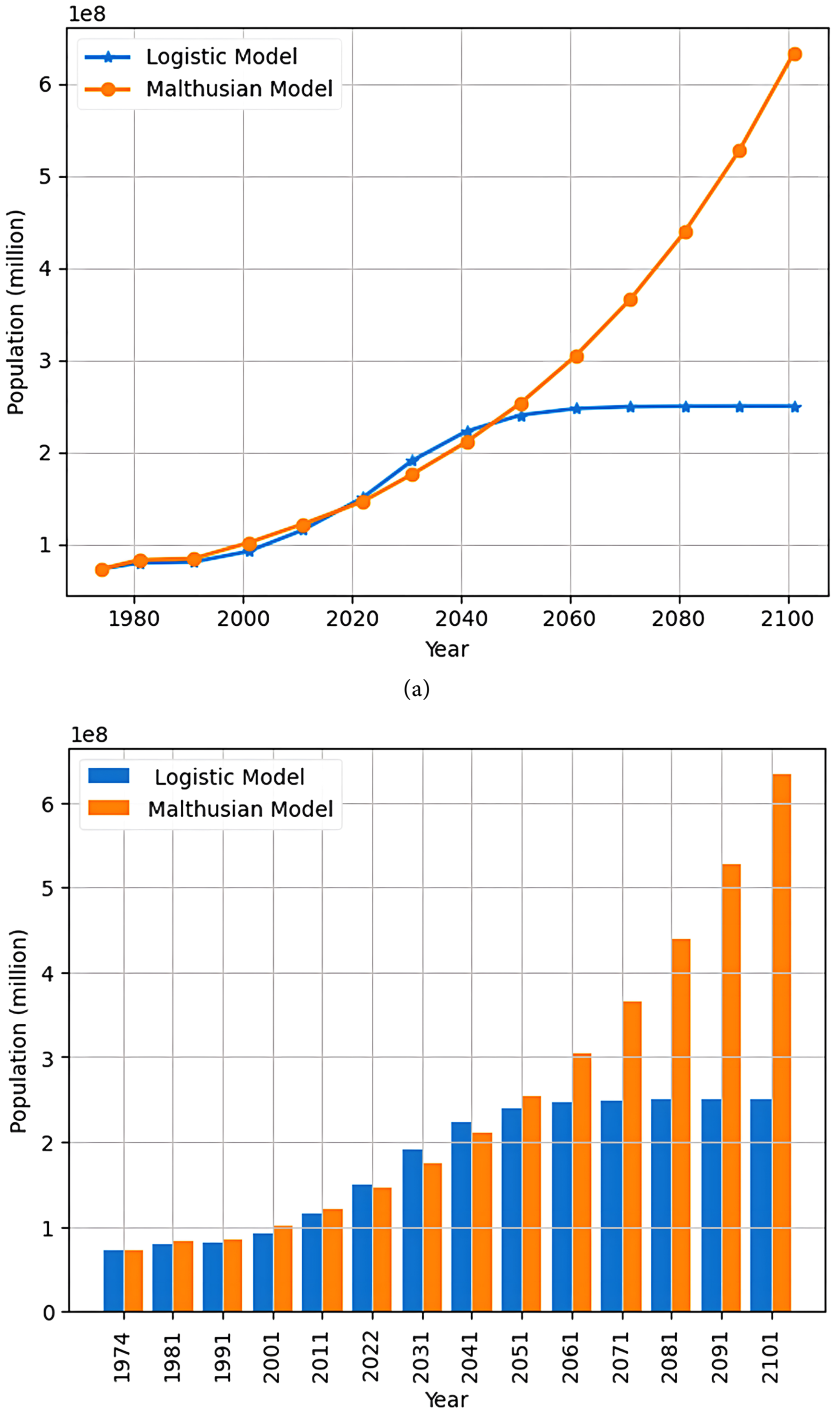
3.2. Predicted Future Population

Here, we forecast the future population of Bangladesh along with the population that already estimated up to 2022 tabulated in Table 1 to compare the predictions of the Malthusian and logistic population to see which one act batter and gives more realistic prediction for population projection.

Table 2. Future population comparison between the Malthusian population model and the logistic population model.

Year	Population According to Malthusian Population Model (Growth rate 1.8315%)	Population According to Logistic Population Model (Growth rate 1.8315%)
1974	72,947,807	72,947,807
1981	82,926,047	79,743,257
1991	84,458,831	80,741,176
2001	101,434,595	92,121,618
2011	121,822,395	115,387,742
2022	146,308,032	150,491,566
2031	175,715,149	190,540,966
2041	211,032,935	222,692,843
2051	253,449,403	240,356,690
2061	304,391,351	247,296,991
2071	365,572,351	249,381,683
2081	439,050,399	249,882,980
2091	527,297,134	249,981,589
2101	633,280,981	249,997,589

Table 2 presents a comparison between the population predictions derived from the Malthusian population model and the logistic population model for the future. Here, we took into consideration 1.8315% as the growth rate for both models and 250,000,000 as Bangladesh's maximum capacity for the logistic population model. The addition of carrying capacity to the logistic population model has culminated in measurable population variations between the two models. In contrast, Bangladesh's population will surpass the carrying capacity in 2061, according to the Malthusian population model, which assumes that the country's population will grow exponentially and without limits in the future, reaching 633,280,981 by the year 2101. However, Bangladesh's population is expected to reach 249,997,589 by the year 2101, approximately half of what the Malthusian population model predicts. This is due to the introduction of carrying capacity.



(a)

(b)

Figure 4. Line and bar graph for future population comparison of the Malthusian population model and the logistic population model.

Figure 4 shows that whereas the logistic population model's predicted carrying capacity prevents future population growth, the Malthusian population model predicts population growth that is limitless over time. It exerts the Malthusian population model in contradiction to the spontaneous growth of any species because a wide range of processes have the potential to sluggish down the expansion of populations. As a result, the Malthusian population model predicts an exponential growth in Bangladesh's population, which is unreal. However, the Malthusian population model's unbounded expansion is constrained due to the addition of carrying capacity, and the logistic population model projects Bangladesh's population to reach 249,997,589 in 2101. This suggests that in case the Malthusian population model is applied, the logistic population model is more realistic.

4. Conclusion

In this work, we utilized data from the Bangladesh Bureau of Statistics (BBS) to evaluate the forecasts of the logistic and Malthusian population models. The logistic model more closely matches the documented population patterns of Bangladesh, even if the Malthusian model provides appropriate predictions for populations with high growth rates over short periods of time. The results indicate that the logistic model is more appropriate for long-term planning, as it provides more accurate population estimation. We found that according to the Malthusian population model, by the year 2051, the population of Bangladesh will cross the maximum population limit of 250,000,000, and after that, the population will increase unboundedly and be estimated to be 633,280,981 in the year 2101. However, from the estimations of the logistic population model, we found that the population of Bangladesh will be 249,997,589 by the year 2101, which is below the population carrying capacity of Bangladesh. Therefore, the logistic population model seems more realistic for predicting future populations than the Malthusian population model. Although none of these models are perfect for estimating population, adding more factors such as migration patterns, socioeconomic conditions, food supply, etc., to these models might provide more accurate forecasts.

Conflicts of Interest

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

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Nomenclature

$N(t)$ = Population at Time t

N_0 = Initial Population

r = Growth Rate

K = Carrying Capacity