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A systematic review of age-structured malaria transmission models (2019–2024)

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Malaria remains a serious and potentially fatal vector-borne disease, consistently ranking among the world's deadliest infections. This study presents a systematic review of age-structured malaria transmission models. Articles were sourced from PubMed, Google Scholar, and the Research Gate Library, resulting in the identification and inclusion of eleven papers in the review. The findings highlight that children under the age of five are more susceptible to malaria than adults, due to their still-developing immune systems. The highest rates of morbidity and mortality are seen in youngsters, pregnant women, and people with impaired immune systems, making age structure a critical factor in the spread of malaria within populations. Personal protection and vector control are key strategies in reducing the transmission of malaria in communities. The study also suggests that the use of fractional operators in modeling could offer new insights into the dynamics of malaria transmission and potential control strategies.

KEYWORDS

malaria, deterministic model, age-structure, control strategies, systematic review

1 Introduction

Malaria remains one of the world's deadliest vector-borne diseases, posing a serious and potentially fatal threat, particularly in tropical and subtropical regions (1). This infectious disease is a significant global cause of morbidity and mortality, often associated with poverty and contributing to the inhibition of economic growth in affected areas (2). Malaria is especially devastating in endemic regions, where it disproportionately impacts children under five, pregnant women, and non-immune adults. According to the World Health Organization (WHO) (3), there were an estimated 249 million cases of malaria and 608,000 deaths worldwide. Children under the age of five accounted for 76% of all malaria-related deaths. Furthermore, 94% of cases and 95% of deaths occurred in the African region, with children under five representing 78% of the fatalities in this region (3).

Malaria is caused by *Plasmodium* parasites, a group of protozoa transmitted primarily through the bites of infected female *Anopheles* mosquitoes (4). Five species of *Plasmodium* infect humans, with *Plasmodium falciparum* being the most prevalent and lethal, particularly in Africa and Southeast Asia (5–7). Symptoms of malaria typically appear within weeks of infection and include fever, chills, sweating, vomiting, abdominal pain, rapid heartbeat, and headaches. Some species of the parasite can remain dormant in the liver, causing relapses months or even years after the initial infection (8). Early diagnosis and treatment are critical for survival, and malaria control strategies, such as insecticide-treated bed nets, anti-malarial medications, and indoor residual spraying, have proven effective in reducing transmission (9–11). While newborns receive temporary immunity from their mothers (12), a multifaceted approach is essential to control the spread of malaria and work toward the ultimate goal of eradicating this preventable disease.

Climatic variability, particularly temperature and rainfall, significantly influences malaria transmission dynamics. Temperature affects both mosquito and parasite behavior (13–17). Higher temperatures lead to more frequent mosquito feeding due to quicker blood digestion (13), but also shorten mosquito lifespan (14). Furthermore, the maturation period of malaria parasites within the mosquito decreases with rising temperatures, from nineteen days at 22°C to eight days at 30°C (16). Temperature fluctuations can also affect malaria transmission rates, either lowering or speeding them up (17). Rainfall plays a crucial role in mosquito breeding and survival (18, 19). While warm, moist conditions in the tropics support stable transmission, excessive rainfall can negatively impact mosquito breeding by flushing away breeding sites (19). Conversely, moderate rainfall can provide suitable breeding habitats for mosquitoes, increasing larval populations (7). These factors demonstrate the complex interplay between climate and malaria transmission, highlighting the need to consider climate variability in public health strategies.

Malaria is preventable and curable, though no single prevention method exists. Various control strategies, including insecticide treated nets (ITNs), treatment of infected individuals, and adulticide, can reduce transmission. Optimal control theory has been applied to identify effective combinations of these strategies, with studies demonstrating the potential for disease eradication using four control strategies such as LLINs, treatment of symptomatic and asymptomatic infections, and IRS (20). A study (21) the cost-effectiveness of optimal control strategies for malaria, considering partial immunity and protected travelers, and incorporating ITNs, prophylaxis, treatment, and vector control.

Vaccination is an effective way of preventing and controlling the prevalence of infectious diseases (22). Recent breakthroughs in malaria vaccines include the WHO's October 2021 recommendation for broad use of RTS and S/AS01 (the first malaria vaccine) in children from moderate to high malaria transmission. In October 2023, the R21/Matrix-M (R21) malaria vaccine became the second vaccine recommended by WHO to prevent malaria in children living in areas of risk (3).

Recently, mathematical models have become increasingly important for understanding infectious disease dynamics (23–25) and remain a powerful tool for controlling infectious diseases like malaria (26–32). Deterministic and stochastic models are used to study transmission mechanisms, design control strategies, and forecast outbreaks (26–32). Early models by Ross and Macdonald highlighted the importance of mosquito control, with Ross suggesting eradication is possible by reducing mosquito populations below a certain threshold (29). Macdonald's model, incorporating an exposed class in the mosquito population, showed that reducing mosquito numbers has limited impact in areas with intense transmission (28). These models introduced the concept of the basic reproduction number which represents the average number of new infections caused by one infected individual (26).

The vulnerability of children under five years to malaria, due to their lack of immunity, makes age structure a significant factor in transmission dynamics (1, 33). Recent models incorporating age-structure have provided insights into control strategies (20, 34–37). Models have highlighted the importance of targeting asymptomatic carriers and utilizing various control measures, including mosquito nets with long-lasting treatment, indoor residual spraying, and the screening and care of both symptomatic and asymptomatic people (20). Other studies have shown that increasing mosquito lifespan and birth rate can lead to higher infection and mortality rates (34). The incorporation of age-structure into models has also been applied to other infectious diseases, such as SARS (38), and has been used to explore the effectiveness of optimal control strategies (39). Further research exploring nonlinear incidence and infection age in malaria transmission has revealed complex interactions that impact the stability of disease states (40).

Fractional calculus, a generalization of classical calculus, has emerged as a valuable tool for modeling real world problems, including infectious disease dynamics (41–47). The most common definitions of fractional derivatives, such as Caputo-fractional and Riemann-Liouville, utilize power decay and derivatives as kernels (41, 45). However, the Atangana-Baleanu and Caputo-Fabrizio operators, with non-singular kernels and non-power law distributions, offer superior modeling capabilities for complex systems, including infectious disease models (42, 43, 46). The Atangana-Baleanu derivative, in particular, is well-suited for modeling real world problems due to its non-singular and non-local kernel properties (42).

Fractional order calculus is increasingly popular for its ability to capture memory effects and hereditary properties present in biological systems, which are not adequately represented by integer-order derivatives (41, 43, 48–50). Models incorporating fractional order derivatives have been developed for malaria transmission, considering factors such as vaccination, anti-malarial drugs, and mosquito control strategies (51–55) and the references therein. This systematic review focuses on age-structured malaria transmission models published between 2019 and 2024.

2 Methods

2.1 Study design

A document analysis review design method was employed in the study.

2.2 Search strategy

A systematic literature search was carried out using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (56). This search was carried out by using the PubMed, Google Scholar, and Research Gate databases from January 2019 and May 30, 2024. We utilized various keywords and Boolean operators in a systematic manner, including "age-structured" OR "class-age structured," as well as "malaria" AND "model*." The Mendeley software was employed to categorize and remove duplicate references (see Figure 1).

2.3 Inclusion and exclusion criteria

- The study used the following inclusion criteria to determine study eligibility:
  - o Deterministic modeling approach.
  - o Articles published in English.

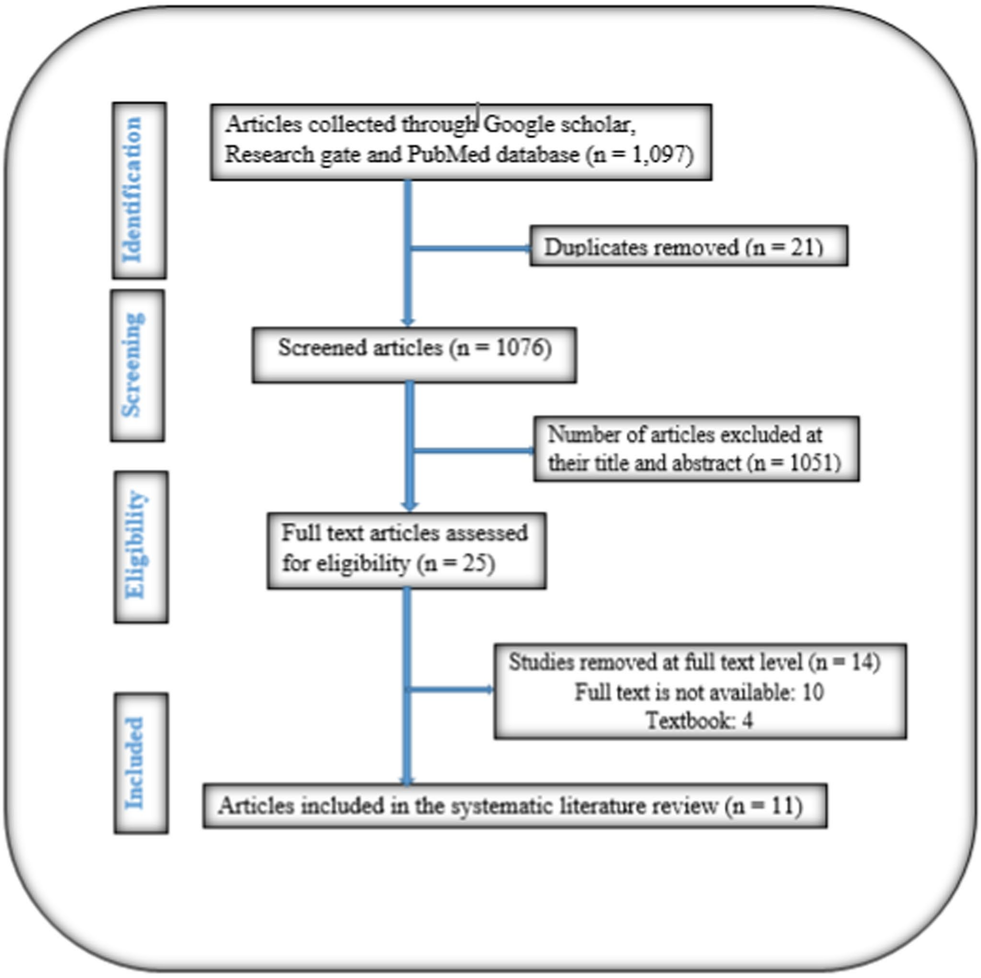

FIGURE 1
PRISMA flow diagram.

  - o Full text of studies available.
  - o Latest published articles from 2019–2024.
  - o Studies indexed by PubMed, Google Scholar, and Research Gate.
- Studies meeting the following criteria were excluded from the review:
  - o Stochastic modeling approach
  - o Article is not published in English
  - o The full text of the study is not available.
  - o Articles published before 2019.
  - o Studies not indexed in PubMed, Google Scholar, and Research Gate.
  - o Text book or book series is not included.

3 Results

By taking into account all of the aforementioned inclusion and exclusion criteria, a database search engine on age-structured malaria models found 1,097 (one thousand ninety-seven) published articles. Following that, a total of 51 (fifty-one) duplicate research articles were eliminated out of a total of 1,097 (one thousand ninety-seven) that were searched. The titles and abstracts of 1,046 (one thousand forty-six) studies were then used to filter them. Ultimately, eleven of the 35 (thirty-five) articles that we had read through to the end were deemed suitable for this systematic review. The included studies are classified as age-structured malaria transmission models, optimal control and cost effectiveness of age-structured malaria transmission models, and fractional order of age-structured malaria transmission models, which are listed in the following Tables 1–3.

4 Discussion

- In order to investigate the dynamics of malaria transmission, Menbiko and Deressa (57) used a mathematical model that included age structure and made use of the Atangana Baleanu fractional derivative. The author included classical and Atangana Baleanu fractional operators in the transmission model details section. The author employed a system of ordinary differential equations along with the SPIR model for the human population and the SI model for the mosquito population. The stability of the endemic and disease-free equilibriums was examined, and the basic reproduction number was calculated. Additionally,

TABLE 1 Age-structured malaria transmission models.

Year	Author	Models	Aims/objectives of the study	Finding/Conclusion
2023	Seck and Ivorra (60)	• SEIR model for humans aged less than sixteen years old. • SEIR model for humans aged greater than sixteen years and above. • LSEI model for the mosquito population	*Investigated the existence, stability, and implications of disease-free and endemic equilibria.* *Conducted numerical simulations to visualize the impact of age structure on malaria transmission dynamics under* various scenarios.	• We analyzed the positivity and boundness of the solutions to our age-structured malaria model. Our results indicate that the solutions are indeed positive and bounded, ensuring biologically meaningful results. • We analyzed the stability of the disease free equilibrium and the endemic equilibrium of our age structured malaria model. • The numerical results are consistent with the theoretical predictions.
2022	Tchoumi et al. (66)	• SEIS model for humans aged less than five years old. • SEIRS model for humans aged greater than five years and above. • SEI model for • the mosquito population	*Investigated the existence and stability of equilibria.* *Conducted numerical simulations that visualize malaria transmission dynamics within the two group structure under various scenarios,*	• The disease-free equilibrium is stable both locally and globally if the basic reproduction number is less than one. The endemic equilibrium is stable both locally and globally if the basic reproduction number is bigger than one. • The numerical results suggest that: • (i) The contact rate between mosquitoes and individuals under five years old has a more pronounced impact on disease transmission than the contact rate between mosquitoes and individuals over five years old. • (ii) Reducing the contact rate between individuals under five years old and mosquitoes leads to a significant decrease in disease prevalence across the entire population. • These findings highlight the importance of targeting interventions, such as increasing access to insecticide treated bed nets and promoting preventive medication use, specifically towards children under five years old. • By focusing resources on this age group, we could potentially achieve more significant gains in reducing malaria transmission and ultimately contribute to achieving eradication goals.
2021	Kalula et al. (62)	• SEIR model for humans aged less than five years old. • SEIAR model for humans aged greater than five years and above. • SEI model for • the mosquito population	*Investigated the impact of asymptomatic carriers on the overall malaria transmission dynamics, emphasizing their contribution to disease persistence and spread within the population.* *Conducted sensitivity analyses on key model parameters.* *Performed numerical simulations to visualize malaria transmission dynamics under various scenarios.*	• We first analyzed a model without infected immigrants. This analysis revealed that the disease free equilibrium exists and is stable when the basic reproduction number, R_0, is less than one. However, the disease-free equilibrium becomes unstable when R_0 exceeds one. • Sensitivity study showed that children's class parameters influenced the basic reproduction number, R_0, more than adult parameters when there were no infected immigrants. However, the model did not show a disease-free equilibrium in the presence of diseased immigrants. • Moreover, a closer look at the endemic equilibrium revealed that the characteristics of asymptomatic carriers were more crucial than those of ill immigrants. • Moreover, the endemic equilibrium was more strongly impacted by the influx of sick people than by specifically diseased immigrants. • Numerical model simulations were carried out in order to verify the previously obtained analytical conclusions concerning the stability of equilibrium points.

(Continued)

TABLE 1 (Continued)

Year	Author	Models	Aims/objectives of the study	Finding/Conclusion
2019	Azu-Tungmah et al. (64)	SIS model for the human population SI model for the mosquitoes population	*Established the existence and stability of equilibria within the model.* *Performed sensitivity analyses on model parameters related to infants and pregnant women.*	• When R_0, the basic reproduction number, is smaller than one, the disease-free equilibrium is locally asymptotically stable. • If the basic reproduction number, R_0, is larger than one, the endemic equilibrium is locally asymptotically stable. • Sensitivity analysis has demonstrated that if the following factors are managed, malaria can be prevented or controlled: biting rates, recruitment rates, mosquito density-dependent natural mortality rates, and human clinical recovery rates.
2019	Guo et al. (63)	• SPEIR model for the human population. • SEI model for the mosquito population.	*Investigated the global stability of the model and established the existence and uniqueness of equilibria. Conducted numerical simulations to visualize the dynamics of malaria transmission across different age groups under different scenarios.*	• We demonstrate the existence of a compact global attractor and derive a sufficient condition for the solution semiflow's uniform persistence. • If the basic reproduction number is less than one, then the disease free equilibrium is globally asymptotically stable. • A distinct endemic equilibrium that attracts all solutions for which malaria transmission occurs exists if the basic reproduction number is greater than one. • Lastly, we can speculate that malaria may eradicated by raising the rate of prevention among susceptible individuals based on the numerical simulations.

numerical simulations are run to investigate the model's behavior for various values of the fractional order alpha. The outcome showed that the endemic spread slows down when the value of α decreases from 1.

- In order to comprehend the dynamics of malaria transmission, Gizaw and Deressa (58) investigated mathematical models using both fractional order and classical (integer order) derivatives. By adding classical and ABC fractional operators, the author expanded on "Analysis of an age structured malaria model incorporating infants and pregnant women." The author employed a system of ordinary differential equations along with the SIS model for the human population and the SEI model for the mosquito population. The basic reproduction number was determined, and the stability of both disease free and endemic equilibrium was explored. Using numerical simulations, the behavior of the model for various values of the fractional order alpha was investigated. The findings showed that when the value α decreases from one, the spread of the endemic grows slower.
- According to Kalula et al. (59), an age-structured deterministic model for malaria transmission that includes symptomatic carriers, temperature variability, and its optimal control and effectiveness was studied. The model was analyzed when temperature-dependent parameters are kept constant and a system of ordinary differential equations is used. The basic reproduction number of the model was determined, as was the stability of both disease-free and endemic equilibrium.
- According to the findings of a sensitivity study, the most sensitive criteria for the basic reproduction number are the rates of mosquito bites and deaths. Furthermore, it has been noted that factors pertaining to individuals under the age of five hold greater significance than those relating to those aged five and above. The recovery rate of carriers who do not exhibit symptoms is also comparatively more significant than the recovery rate of persons who do exhibit symptoms. As a result, efforts to lower mosquito bite rates and raise mosquito mortality rates have a bigger effect on lowering the spread of disease.
- Controlling the condition in children and carriers who exhibit symptoms will also have a significant impact. Numerical simulations of the optimal control problem indicate that treating symptomatics, treating asymptomatic carriers, implementing long-lasting insecticide nets, and insecticide spraying is the most effective strategy for reducing the number of infected individuals. The cost-effectiveness analysis also shows that treating symptomatic patients, identifying and treating asymptomatic carriers, and applying pesticide spraying are the most cost-effective ways to stop the spread of malaria in scenarios where resources are limited.
- Seck and Ivorra (60), studied a mathematical model to understand how malaria spreads within a population, specifically considering the influence of age on disease transmission. The author employed a system of ordinary differential equations along with the LSEI model for the mosquito population and the SEIRS model for the human population. The next-generation matrix approach was used to calculate the fundamental reproduction number, and the stability of the endemic and disease-free equilibrium was examined.
- Tchoumi et al. (2022), conducted a theoretical analysis and formulation of a two group malaria model structured by age,

TABLE 2 **Optimal control and cost effectiveness of an age-structured malaria transmission model.**

Year	Author	Models	Aims/objectives of the study	Finding/Conclusion
2023	Kalula et al. (59)	• SEIR model for children under five years old. • SEIAR model for individuals who are five years of age or older. • SEI model for mosquito population.	*Applied optimal control strategies aimed at minimizing malaria transmission and disease burden.* *Conducted numerical simulations to evaluate the dynamics of malaria transmission under different intervention scenarios and temperature conditions, aiding in understanding the potential outcomes of various control strategies.*	• If the basic reproduction number, R_0, is less than one, then the disease-free equilibrium point is both locally and globally stable, otherwise unstable. • A sensitivity study for the parameters influencing the basic reproduction number was conducted. The outcomes showed the most sensitive parameters were death rates and mosquito biting rates. Furthermore, parameters pertaining to young children (under five years old) were found to be more significant than those for individuals five years of age and older. • Likewise, the rate of recovery of asymptomatic carriers was more influential than the recovery rate of symptomatic individuals. These findings suggest that interventions aimed at reducing mosquito biting rates and increasing mosquito mortality would have a substantial impact on reducing disease transmission. • Additionally, managing the disease in children and asymptomatic carriers would yield significant benefits in mitigating the spread of malaria. • Variability in temperature's impacts have been studied, and the findings indicate that when seasonality is absent, the ideal cumulative malaria new case accumulation occurs at a temperature between 24.78 and 26.78 degrees Celsius. • So, the number of new cases of cumulative malaria has decreased at temperatures below or above this range. • The approach that uses all four controls (long lasting insecticide nets, treating symptomatics, screening and treating asymptomatic carriers, and insecticide spraying) together is the most successful in lowering the number of infected people, according to numerical simulations of the optimal control problem. • Furthermore, the cost effectiveness study shows that treating symptomatic patients, treating asymptomatic carriers, and using pesticide spraying are the most cost-effective ways to stop the spread of malaria in scenarios where resources are limited.
2022	Tchoumi et al. (67)	• SVEI model for individuals under five years of age. • SEIR models for people who are older than five years old. • SEI model for mosquito population	*Investigated the existence and stability of equilibria.* *Applied optimal control strategies aimed at minimizing malaria transmission and disease burden.* *Conducted numerical simulations to visualize and analyze the impact of different vaccination strategies and coverage levels on malaria transmission dynamics.*	• When the death rate from disease occurs in both human groups is zero, the disease-free equilibrium is globally asymptotically stable. • If the death rate caused by the disease is not zero, then the condition for the basic reproduction number being less than one is insufficient to maintain the global stability of the disease free equilibrium, and backward bifurcation may happen. • The most effective set of intervention methods to slow the spread of malaria was looked into using the optimal control theory. • Compared to employing a single or any dual combination of intervention(s) at a time, the numerical simulation results demonstrate that the best strategy for combating the malaria epidemic in a community is to apply the three intervention measures personal protection, treatment, and vaccination of children under five concurrently.

(Continued)

TABLE 2 (Continued)

Year	Author	Models	Aims/objectives of the study	Finding/Conclusion
2021	Wang et al. (61)	• SVIR model for the human population. • SI model for the mosquito population.	*Performed a global stability analysis of the model.* *Applied an optimal control problem aimed at minimizing malaria transmission and maximizing health outcomes through the strategic deployment of vaccination and management of relapse cases.* *Implemented numerical simulations to investigate the dynamical behavior of the model under various scenarios.*	• The disease free equilibrium is globally asymptotically stable and the disease disappears if the basic reproduction number, R_0, is less than one, while the endemic equilibrium is globally asymptotically stable and the disease persists consistently if the basic reproduction number, R_0, is greater than one, resulting in an endemic disease. • The control measures represented by prevention (surveillance, use of mosquito nets, treating mosquito-breading ground) are used more often at the beginning of the outbreak, while the control measures represented by larvacide and adulticide will be used more often during the epidemic period. • This implies that insecticide spraying during the epidemic period will be more effective than preventive measures to control the disease. • Thus, achieving the eradication of malaria disease, it should also take many preventive measures in advance throughout the early stage of the disease outbreak, such as vaccination protection, use of mosquito nets. • Finally, the combination with insecticide spraying will be more effective in controlling the disease.
2019	Azu-Tungmah et al. (65)	• SIS model for the human population. • SI model for the mosquito population.	*Investigated the existence and stability of disease-free and endemic equilibrium.* *Performed sensitivity analyses on key model parameters.* *Conducted numerical simulations to visualize the impact of age structure and vulnerabilities of children and pregnant women on malaria transmission dynamics under various intervention scenarios.* *Assessed the cost-effectiveness of implemented control strategies.*	• The effective reproduction number, R_e, has been derived by using the next-generation matrix method. • When the effects of the four controls (insecticide treated bed nets, indoor residual spraying, chemoprophylaxis, and improved clinical treatment were examined, it was shown that each control had a beneficial effect on R_e). • The optimal result revealed that the combination of improved clinical treatment, chemoprophylaxis, and insecticide-treated bed nets is the most effective control strategy for eliminating malaria. • However, the cost-effectiveness analysis points out that insecticide-treated bed nets is economically best solution for fighting malaria in poor malaria endemic areas.

wherein individuals under five years old receive vaccine. The author employed a system of ordinary differential equations, the SVEI and SEIR models in the human population, and the SEI model in the mosquito population. The next generation matrix approach was utilized to calculate the basic reproduction number. When the disease induced death rate in both human groups is zero, the disease free equilibrium is globally asymptotically stable; otherwise, backward bifurcation may happen. The outcomes of the numerical simulation showed that the three intervention measures personal protection, treatment, and vaccination of children under five should be implemented concurrently in order to effectively combat the malaria outbreak in a community.

- Tchoumi et al. (66), studied how malaria spread within a population that was divided into two distinct groups. They used the SEI(R)S model for the human population, the SEI model for the mosquito population, and a system of ordinary differential equations. The next generation matrix approach was used to calculate the basic reproduction number, and equilibrium stability was explored. On the other hand, when an endemic equilibrium coexists with a disease free equilibrium, the model may display the phenomena of backward bifurcation under specific circumstances. According to the numerical result, there is a greater sensitivity in the contact rate between mosquitoes and people under five years old than there is between mosquitoes and people over five. Lastly, increasing the effort to combat malaria in children under five has a higher effect on reducing the disease's spread throughout the population, which may result in better progress toward the disease's eventual mitigation and eradication.
- Wang et al. (61), examined how to understand and manage malaria transmission using a mathematical model that integrates

TABLE 3 Fractional order on age-structured malaria transmission model.

Year	Author	Models	Aims/objectives of the study	Finding/Conclusion
2024	Gizaw and Deressa (58)	SIS model for the human population SEI model for the mosquito population.	*Investigated the existence and stability of equilibria within the age-structured model using both classical and ABC fractional operators.* *Conducted sensitivity analyses on key parameters to identify the factors most significantly affecting malaria transmission dynamics, and performing numerical simulations to visualize and compare these dynamics under various intervention scenarios using both classical and fractional modeling approaches.*	• If the basic reproduction number, $R_{0,}$ is lessthan one, then the disease free equilibrium is both locally and globally asymptotically stable. • If the basic reproduction number, $R_{0,}$ is greater than one, then the endemic equilibrium is both locally and globally asymptotically stable. • Sensitivity study showed that the mosquito bite rate, density-dependent natural fatality rate, clinical recovery rate, and mosquito recruiting rate are the most sensitive factors that are crucial for reducing or eliminating malaria. • Numerical Simulations showed that decreasing the fractional order alpha (α) from one slows the spread of the endemic.
2024	Menbiko and Deressa (57)	Model of SPIR for the human population SI model for the of mosquito population.	*Investigated the existence and stability of equilibria.* *Implemented numerical simulations to visualize transmission dynamics under the influence of age structure and fractional derivatives, and compared these results with classical models.*	• If the basic reproduction number, $R_{0,}$ is less than one, then the disease free equilibrium is both locally and globally asymptotically stable. • If the basic reproduction number, $R_{0,}$ is greater than one, then the endemic equilibrium is both locally and globally asymptotically stable. • Numerical simulations were also performed to examine the behavior of the model for different values of the fractional-order alpha, and the results revealed that as the value of α reduced from one, the spread of the endemic grew slower.

age structure, immunization, and the occurrence of relapse. The author employed a system of ordinary and partial differential equations, the SVIR model for the human population, and the SI model for the mosquito population. The basic reproduction was calculated, and the disease free equilibrium was both locally and globally asymptotically stable, otherwise unstable, because the basic reproduction number is smaller than unity. According to the numerical result, controlling the disease in combination with insecticide spraying will be more successful.

- According to Kalula et al. (62), malaria spreads in a population, considering the influence of age, infected immigrants, and asymptomatic carriers. The author used the SEI(A)R model for the human population, the SEI model for the mosquito population, and a system of ordinary differential equations. The basic reproduction number was computed, and the stability of the disease-free and endemic equilibrium was discussed. Besides, the sensitivity of the basic reproduction number shows that children's class parameters are more sensitive than those of adults. In the presence of infected immigrants, the model does not admit a disease-free equilibrium. The numerical results indicate that the asymptomatic carriers have more impacts than the infected immigrants on malaria dynamics.
- Using a mathematical model, Guo et al. (63) investigated the long-term (global) effects of preventive measures on malaria transmission while taking into account the distinct vulnerabilities of different age groups. The author used the SPEIR model for the human population and the SEI model for the mosquito populations, and the model was described as a system of both ordinary and partial differential equations. The author clearly explained well-posedness and uniform persistence. The basic reproduction number was computed, and both local and global stability were discussed. Finally, the author concluded that the basic reproduction number decreased as the rate of prevention increased; that is, increasing the degree of prevention could lead to malaria becoming extinct.
- Azu-Tungmah et al. (64, 65) investigated how the prevalence of malaria in humans varies with age and gender. The author did an extension of "Analysis of an age-structured malaria transmission model" or Wang et al. (36) by incorporating an infectious compartment for pregnant women and avoiding the recovered compartment from Addawe and Lope's model. The author used the SIS model for the human population, the SI model for the mosquito population, and a system of ordinary differential equations. The basic reproduction number confirmed that the disease-free and endemic equilibrium is both locally and globally stable. Sensitivity analysis has proved that malaria can be controlled or eliminated if the following parameters are controlled: biting rates, recruitment rate, density-dependent natural mortality rate for mosquitoes, and clinical recovery rates for humans.
- The most effective and efficient methods of preventing malaria transmission were investigated by Azu-Tungmah et al. (64, 65), with a particular emphasis on the special vulnerability of pregnant women and children under five. By including optimal control, the author expanded on "Analysis of an age structured malaria model incorporating children under five years and pregnant women." For the human population, the author employed the SIS model, and for the mosquito population, the SI

model. The system of ordinary differential equations was used to define the model. The next generation approach was used to determine the effective reproduction number. The impact of the controls was examined, and it was found that each of the four controls had a positive effect.

5 Conclusion

This systematic review examined the transmission dynamics of malaria in age-structured populations, revealing the crucial role of age in shaping disease spread. Children under five, due to their weaker immune responses, are significantly more susceptible to malaria than adults. The highest rates of morbidity and mortality are seen in youngsters, pregnant women, and people with impaired immune systems. The distribution of age groups plays a crucial role in the spread of malaria within communities, with different age groups contributing uniquely to transmission patterns. Moreover, effective control strategies including personal protection methods, targeted treatment regimens, and vector control interventions have demonstrated a substantial impact in reducing malaria transmission. The application of fractional operators in mathematical models offers further insights into the complexities of malaria transmission and may provide new approaches for optimizing control strategies. Overall, this review underscores the intricate relationship between age structure, demographic factors, and control measures in shaping malaria transmission dynamics. These findings provide valuable guidance for public health efforts aimed at minimizing the global malaria burden.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DD: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. TK: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. CD: Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

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