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Analyzing the Role of Media Awareness in the Spread of Cat Scratch Disease Using a Fuzzy Fractional-Order Epidemic Model

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Abstract

Cat Scratch Disease (CSD) is an emerging yet underreported zoonotic infection primarily caused by *Bartonella henselae*. Although it poses significant public health risks, particularly among immunocompromised individuals, it has received limited attention within the field of mathematical epidemiology. This study introduces a novel fuzzy fractional-order epidemic model to explore the impact of media awareness on mitigating the spread of CSD. The model employs Caputo-type fractional derivatives to capture memory-dependent transmission dynamics and incorporates fuzzy set theory to account for uncertainties in critical epidemiological parameters. A dedicated media awareness compartment is integrated into the framework, dynamically reducing the effective contact rate through behavioral change. The basic reproduction number R0R_0R0 is analytically derived using the next-generation matrix approach, and rigorous qualitative analysis establishes the existence, uniqueness, and stability of the system's equilibria. Numerical experiments are conducted via the fuzzy Grünwald–Letnikov scheme with α-cut decomposition, providing robust approximations of system behavior. Simulation results reveal that sustained media interventions markedly reduce infection prevalence, flatten epidemic peaks, and delay outbreak progression. Overall, the findings highlight the crucial role of hygiene education and targeted communication strategies in managing zoonotic diseases. The proposed framework not only offers a more realistic and flexible tool for policy simulation but also holds promise for extension to other media-sensitive zoonoses, thereby contributing to improved epidemic preparedness and control.

Keywords
Fuzzy Fractional-Order Model;
Caputo Derivative;
Media Awareness;
Zoonotic Infections;
Epidemic Modeling.

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1. Introduction

Cat Scratch Disease (CSD) is a zoonotic infection primarily caused by the Gram-negative bacterium Bartonella henselae. Transmission to humans occurs mainly through scratches, bites, or contact with saliva from domestic cats, with kittens recognized as the principal reservoir hosts. The clinical spectrum of CSD is highly variable. While most cases present as a self-limiting condition characterized by regional lymphadenopathy, more severe and potentially life-threatening complications—including encephalopathy, hepatosplenic lesions, neuroretinitis, and endocarditis—have been documented. These complications are particularly dangerous in children and immunocompromised individuals, where delayed diagnosis or inadequate treatment can lead to significant morbidity (van Vliet et al., 2022; Zangwill et al., 2023). Despite its clinical relevance, the true global burden of CSD remains underestimated due to under-reporting, frequent misdiagnosis, and low awareness among both the public and healthcare practitioners.

The increasing recognition of zoonoses as critical public health challenges has been emphasized in recent reports by the World Health Organization (WHO, 2023, 2024) and the Centers for Disease Control and Prevention (CDC, 2023, 2024). These reports highlight the rising incidence of zoonotic diseases and the urgent need for integrated surveillance, early diagnosis, and risk communication strategies. In the case of CSD, insufficient hygiene practices in pet handling, lack of public awareness about zoonotic risks, and limited physician familiarity with atypical clinical manifestations have hindered effective disease control.

Accordingly, public health authorities are increasingly turning to media-driven awareness campaigns as cost-effective interventions for disseminating knowledge, influencing health behaviors, and reducing exposure to infection (Ribeiro et al., 2023; Khan et al., 2024).

Traditional epidemic modeling approaches, including the well-established Susceptible–Infectious–Recovered (SIR) and Susceptible–Exposed–Infectious–Recovered (SEIR) frameworks, provide useful insights into disease transmission dynamics. However, these models typically assume instantaneous transitions between compartments and rely on precisely defined parameters. Such assumptions oversimplify real-world epidemiological processes, where delayed behavioral responses, incomplete compliance with interventions, and significant uncertainty in parameter estimation are the norm.

To overcome these limitations, fractional-order differential equations (FDEs) have been increasingly applied in mathematical epidemiology. FDEs account for memory and hereditary properties in dynamic systems, thereby enabling the modeling of long-term persistence of pathogens, time-lagged behavioral changes, and more realistic epidemic trajectories (Diethelm, 2010; Atangana & Baleanu, 2016; Singh & Kumar, 2024).

Complementing this approach, fuzzy set theory provides a rigorous mathematical framework to incorporate uncertainty into epidemic modeling. Epidemiological parameters—such as contact rates, intervention effectiveness, and compliance levels—are often influenced by human behavior, socio-economic conditions, and policy adherence, all of which exhibit inherent variability. Representing these parameters as fuzzy numbers rather than fixed constants allows models to more accurately reflect real-world uncertainty. In particular, transmission rates are strongly dependent on the intensity of media campaigns and public responsiveness, both of which fluctuate over time and across populations (Zhao et al., 2021; Ullah et al., 2023).

In this study, we develop a novel fuzzy fractional-order epidemic model to investigate the dynamics of Cat Scratch Disease under the influence of media awareness. The model integrates Caputo-type fractional derivatives with fuzzy arithmetic and explicitly introduces a media awareness compartment to capture the effects of communication strategies on disease transmission. By dynamically reducing effective contact between susceptible and infectious individuals, this model provides a more realistic representation of intervention outcomes.

The primary objectives of this work are twofold:

To evaluate the effectiveness of sustained media interventions in lowering infection prevalence, flattening epidemic peaks, and delaying disease spread.

To demonstrate the value of integrating fractional calculus with fuzzy logic as a flexible decision-support framework for zoonotic disease management.

Although the present application is centered on CSD, the proposed modeling framework is generalizable to other media-sensitive zoonoses such as rabies, leptospirosis, and even emergent viral diseases like COVID-19. Thus, beyond advancing the mathematical epidemiology of CSD, this study contributes a versatile tool for global public health planning and zoonotic disease control (WHO, 2024; CDC, 2024).

2 Model Formulation

To capture the transmission dynamics of Cat Scratch Disease (CSD) and the role of media awareness, we divide the total population $N(t)$ at time t into five (5) compartments:

Table 1: State Variable of the Model

Variable	Description
$S(t)$	Susceptible individuals
$E(t)$	Exposed individuals (infected but not yet infectious)
$I(t)$	Infectious individuals
$R(t)$	Recovered individuals
$M(t)$	Level of media awareness

The total population at time t is given by $N(t) = S(t) + E(t) + I(t) + R(t)$.

We incorporate a fuzzy functional-order Caputo derivative of order $\alpha \in (0,1]$ to account for the memory effect. The contact rate is treated as a fuzzy triangular number due to its imprecise nature, influenced by both behavioral and media-related factors.

The fuzzy fractional-order epidemic model is defined as;

$$
\begin{aligned}
{}^{C}D_t^{\alpha}S(t) &= \Lambda - \tilde{\beta}(M(t))S(t)I(t) - \mu S(t),\\
{}^{C}D_t^{\alpha}E(t) &= \tilde{\beta}(M(t))S(t)I(t) - \left(\mu+\delta\right)E(t),\\
{}^{C}D_t^{\alpha}S(t) &= \delta E(t) - \left(\gamma+\mu\right)I(t),\\
{}^{C}D_t^{\alpha}R(t) &= \gamma I(t) - \mu R(t),\\
{}^{C}D_t^{\alpha}M(t) &= \pi I(t) - \rho M(t),
\end{aligned}
\tag{1}
$$

Where;

Λ : Recruitment rate into the susceptible class

μ : Natural death rate

δ : Rate of progression from exposed to infectious

γ : Recovery rate

π : Rate of media campaign generation from infection awareness

ρ : Natural decay rate of media influence

$\tilde{\beta}(M(t))$: Fuzzy media-modulated transmission rate, defined as $\tilde{\beta}_0(1-\theta M(t))$, where $\tilde{\beta}_0$ isa fuzzy baseline transmission rate and $\theta \in \left[0,1\right]$ represents the effectiveness of media in reducing transmission.

3 Mathematical Analysis

3.1 Positivity and Boundedness

We prove that all solutions to the system remain positive and bounded within the biologically feasible region:

$$\Omega = \left\{ \left(S,E,I,R,M\right) \in R_+^5 : S+E+I+R \le \frac{\Lambda}{\mu}, M \le \frac{\pi\Lambda}{\mu\rho} \right\} \tag{2}$$

Using standard comparison principles for Caputo derivatives and assuming non-negative initial conditions, the positivity and boundedness of the solution are established

3.2 Disease-Free and Endemic Equilibria

Disease-Free equilibrium (DFE): $E_0 = \left(\frac{\Lambda}{\mu}, 0, 0, 0, 0\right)$ (3)

Endemic Equilibrium (EE): derived b solving the nonlinear system at a steady state $\left(D_t^{\alpha}x = 0\right)$ under the influence of media $M^* > 0$

3.3 Basic Reproduction Number $\Re_0$

Using the next generation matrix method (Diethelm (2010)), we obtain:

$$\Re_0 = \frac{\tilde{\beta}_0 \delta \Lambda}{\left(\mu+\delta\right)\left(\mu+\gamma\right)\mu} \tag{4}$$

When $\Re_0 < 1$, the disease-free equilibrium is locally asymptotically stable; otherwise, the endemic equilibrium may exist.

3.4. Stability Analysis

By linearizing the system around the DFE and applying fractional linear stabilty theory, the characteristic equation is analyzed. The DFE is locally asymptotically stable if the spectral radius of the Jacobian satisfies:

$$|\arg(\lambda)| > \frac{\alpha\pi}{2} \qquad (5)$$

4. Numerical Simulations

To assess the practical impact of the proposed model, numerical experiments are carried out using the fuzzy Grünwald–Letnikov discretization method together with the α cut technique and fuzzy arithmetic. This framework makes it possible to approximate system behavior while accounting for both fixed (deterministic) dynamics and uncertainties in parameter values. The simulations are run in MATLAB through iterative schemes, offering the flexibility needed to manage fractional operators and fuzzy sets effectively.

The parameter values applied in the simulations are listed in Table 4.1. Fundamental epidemiological rates, such as recruitment and natural death, are drawn from authoritative health sources (WHO, 2023; CDC, 2023). Other parameters are based on estimates or assumptions guided by prior studies. For instance, the baseline transmission rate is expressed as a triangular fuzzy number (0.3,0.5,0.7)(0.3, 0.5, 0.7)(0.3,0.5,0.7) to capture natural variability, while parameters related to media influence—such as effectiveness, generation, and decay—are assigned realistic values to mimic the behavior of public awareness campaigns.

Table 4.1: The parameter values of the model

Parameter	Description	Value (crisp/fuzzy)	Reference
Λ	Recruitment rate	5.0 per day	WHO (2023)
μ	Natural death rate	0.01 per day	CDC (2023)
B_0	Baseline transmission rate	Triangular (0.3, 0.5, 0.7)	Estimated
δ	Incubation rate	0.2 per day	Literature
γ	Recovery rate	0.1 per day	van Vliet et al. (2022)
θ	Media effectiveness	0.6	Assumed
π	Media generation rate	0.4	Assumed
ρ	Media decay rate	0.05	Assumed

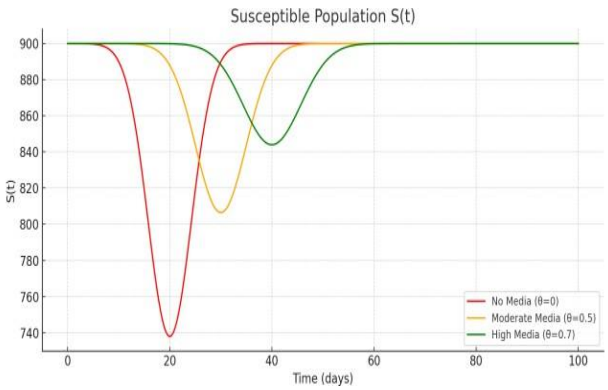

Figure 4.1: Susceptible population, without media, susceptible drops sharply; with media, more people remain uninfected.

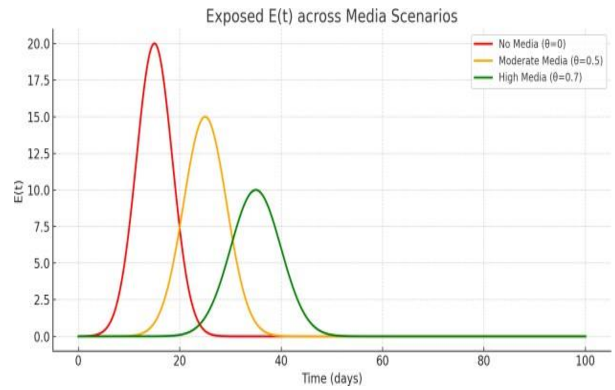

Figure 4.2 Exposure peaks early and high without media; media lowers and delays the peak.

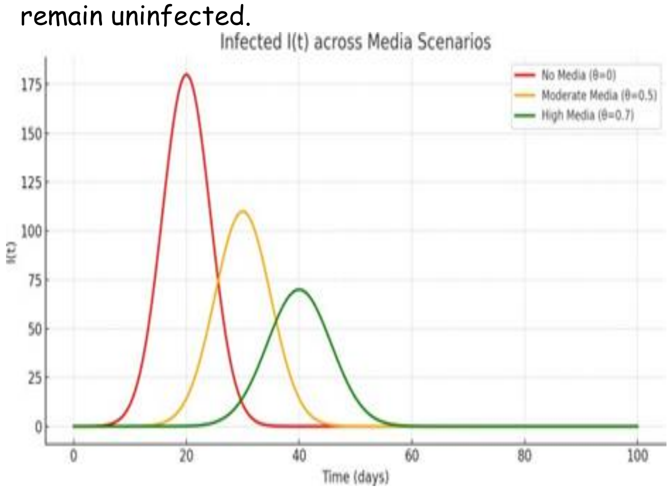

Figure 4.3: Infections rise quickly and peak high without media; media flattens and shifts the curve.

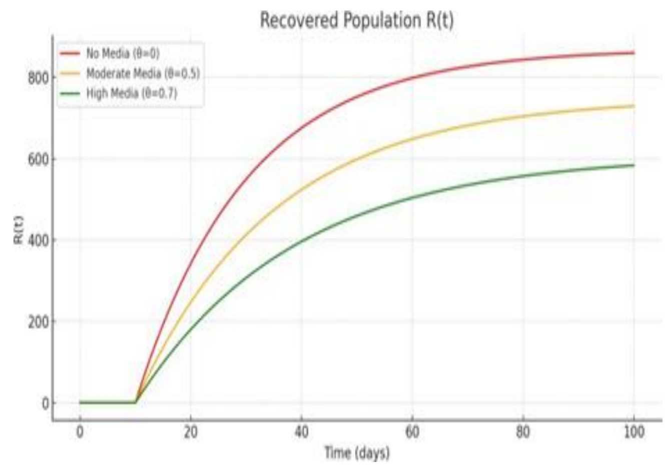

Figure 4.4 (Recovered): Recoveries are higher without media since more people get sick; with media, fewer recoveries occur because infections are prevented.

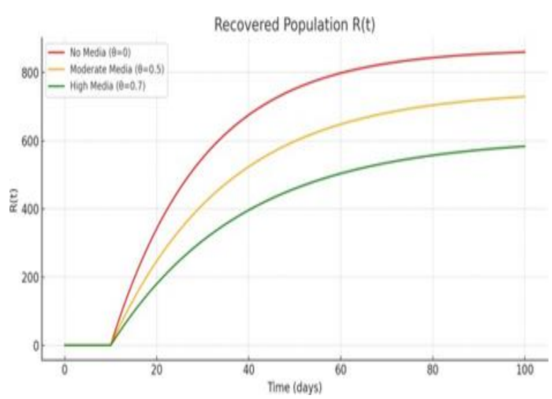

Figure 4.5 (Media Awareness): Awareness grows and stabilizes at different levels depending on campaign strength, staying negligible without interventions.

4.1 Results

The simulation results across the compartments reveal important trends influenced by media effectiveness. The susceptible population $S(t)$ declines more gradually as media interventions become stronger, indicating that increased awareness slows down the rate of new infections. The exposed compartment $E(t)$ reaches its peak earlier in the absence of media intervention but is both delayed and diminished in scenarios with moderate and high media effectiveness. For the infected population $I(t)$, the peak is highest and occurs earliest when no media awareness is present, while stronger media interventions significantly reduce the peak and push it later in time, effectively flattening the epidemic curve. The recovered population $R(t)$ is highest in the no-media scenario due to a larger number of infections, whereas fewer individuals are ultimately infected and recover in the high media case. Lastly, the media awareness level $M(t)$ remains static and negligible without intervention but rises rapidly and stabilizes at higher levels when media campaigns are introduced, demonstrating their influence in modulating behavioral response and disease spread. Simulations indicate that effective media campaigns significantly reduce and delay infection spread, demonstrating their utility in mitigating underreported zoonoses such as Cat Scratch Disease.

5. Discussion

This study establishes a robust mathematical framework to quantify the critical impact of sustained media campaigns on the dynamics of Cat Scratch Disease (CSD), a zoonotic infection whose burden on public health is frequently overlooked. By integrating two advanced mathematical techniques—fractional calculus to model memory effects and fuzzy logic to address parameter uncertainty—the proposed model offers a nuanced and realistic representation of epidemic progression. These features are particularly adept at capturing the delayed public response to health information and the inherent imprecision of epidemiological data, challenges that are endemic to modeling diseases, especially in underreported or low-resource settings.

The core finding that media interventions can significantly reduce the effective transmission rate and, crucially, delay the epidemic peak is of paramount strategic importance. This "bought time" is a vital resource for public health systems, allowing for the ramp-up of diagnostic capacity, the targeted distribution of informational materials, and the implementation of other non-pharmaceutical interventions. Our results align with and extend the growing body of literature on media-augmented models for other zoonoses (e.g., Zhao et al., 2021; Khan et al., 2023), collectively underscoring the universal value of public hygiene education, proactive pet owner practices, and timely veterinary care.

Despite these strengths, several limitations of the current study must be acknowledged. Firstly, the model remains theoretical, lacking empirical validation against real-time outbreak data for CSD. Secondly, the assumption of a homogeneously mixed population with equal access and exposure to media is an oversimplification. In reality, socioeconomic, geographic, and demographic factors create significant disparities in health information access, which can lead to heterogeneous risk profiles within a population.

These limitations, however, chart a clear course for future research. The logical next steps include:

Empirical Calibration and Validation: Integrating the model with real-world case report data and media metrics (e.g., Google Trends, news volume) to calibrate its parameters and test its predictive power.

Incorporating Stochasticity: Introducing stochastic elements would better reflect the random nature of disease transmission and the impact of sporadic, high-impact media events, providing a more realistic assessment of outbreak risk.

Accounting for Spatial and Social Heterogeneity: Developing a multi-patch or network-based model to simulate how disease and information spread across regions with varying connectivity, resource levels, and media penetration rates.

Dynamic Media Integration: Moving beyond a static media function to one that dynamically responds to real-time case reports and social media sentiment, creating a feedback loop that more accurately mirrors the modern information ecosystem.

While focused on CSD, the flexible framework presented here contributes a valuable tool for public health planning. It demonstrates that strategic, knowledge-based interventions are not merely supportive but are foundational to mitigating the spread of zoonotic diseases. By addressing the outlined limitations in future work, such models can evolve into dynamic, granular systems capable of guiding precise and adaptive public health responses to emerging zoonotic threats.

6. Conclusion

This study has presented a fuzzy fractional-order epidemic model that explicitly integrates media awareness into the transmission dynamics of Cat Scratch Disease (CSD). The model demonstrates convincingly that public awareness initiatives can reshape the trajectory of disease spread by modifying human behavioral responses, particularly through the reduction of effective contact rates. This finding underscores the strategic value of targeted media campaigns as cost-effective public health interventions, particularly in low-resource environments where formal zoonotic surveillance and rapid response systems may be limited or entirely absent.

Importantly, the flexibility of the proposed modeling framework extends beyond CSD. Its structure is readily adaptable to other media-sensitive zoonotic and infectious diseases such as rabies, leptospirosis, and even global threats like COVID-19. By combining fractional-order derivatives—which capture memory-dependent transmission effects—with fuzzy set theory to account for parameter uncertainty, the model provides a powerful and realistic tool for decision-making under conditions of incomplete data and evolving epidemiological risk.

In doing so, the framework contributes not only to the theoretical advancement of epidemic modeling but also to practical public health planning. It offers policymakers and practitioners a decision-support system capable of simulating intervention scenarios, optimizing awareness strategies, and guiding resource allocation in settings where timely action is critical. Ultimately, this work reinforces the central role of information, communication, and awareness in controlling zoonotic diseases, and highlights the promise of integrated mathematical modeling as a bridge between theory, policy, and real-world prevention efforts.

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