

Analysis and implementation of a numerical technique for solving fractional Blood Alcohol model

N. Kalyan, S. Ahuja and A. Prakash

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Corresponding Author: A. Prakash

Abstract In this paper, we explore the alcohol level dynamics in the body of an individual using a fractional model. By incorporating the Caputo fractional derivative, the traditional model is expanded into the fractional model. The Banach fixed point theorem and the Ulam-Hyers condition are defined for the existence, uniqueness and the stability of the solution, respectively. Numerical simulations are performed using a hybrid method, Modified Adams-Bashforth Moulton method, with results presented in both tabular and graphical formats. The accuracy of the numerical solution is evaluated by comparing with the exact solution and with the existing technique by using the Root Mean Square error. The numerical results demonstrate the effectiveness of the proposed approach in handling the fractional differential equations.

1. Introduction

The study of fractional calculus [1], which involves arbitrary order derivatives and integrals, has garnered significant attention in recent years, because of its ability to model complex physical and biological processes more precisely. Unlike classical calculus, which focuses on integer-order derivatives, fractional calculus provides a more comprehensive framework for capturing the memory that exist in real-world systems. This feature makes fractional differential equations valuable for modelling phenomena in a variety of fields, including engineering, biology, and physics. Fractional-order models have proven to be more flexible and realistic in describing processes with nonlocal behavior, in which the future values of a system is computed by both its current and previous behavior [2]. As a result, these models provide a richer and more precise depiction of dynamic systems than the classical models. Numerous numerical and analytical techniques for solving fractional differential equations have evolved over time, including the Residual Power Series Method (RPSM) [3–5], Laplace Iterative Method (LIM) [6, 7], Adams-Bashforth method [8, 9], Adams-Bashforth Moulton method [10], and others.

Alcohol is a toxic substance that can lead to addiction. In modern societies, many individuals regularly consume alcoholic beverages. The liver plays a role in metabolizing alcohol through enzymes, but it can only process a limited amount at a time, allowing the excess alcohol to circulate throughout the body. As reported by the World Health Organization (WHO) [11], unhealthy alcohol consumption causes 3 million deaths annually. Furthermore, dangerous consumption of alcohol has been linked to over 200 illnesses and also accounts for 13.5% of deaths among those aged 20-39. Ludwin [12] initially addressed this issue by solving a differential system to model the concentration of alcohol in blood over time.

$$\left. \begin{aligned} \frac{dS}{dt} &= -k_1 S(t), \\ \frac{dB}{dt} &= k_1 S(t) - k_2 B(t), \end{aligned} \right\} \quad (1.1)$$

with the initial conditions as

$$S(0) = S_0, \quad B(0) = 0.$$

The exact solution for system of equations (1.1) by direct integration is as follows [12]:

$$S(t) = S_0 e^{-k_1 t},$$

$$B(t) = S_0 \left(\frac{k_1}{k_2 - k_1} \right) (e^{-k_1 t} - e^{-k_2 t}),$$

and, the exact values of alcohol level in blood with respect to time is shown by table 1.

Table 1. Exact solution of alcohol concentration.

Time in minutes	Blood alcohol concentration (mg/L) [12]
0	0
10	147.54
20	172.95
30	161.38
45	129.99
80	70.99
90	59.49
110	41.74
170	14.41

The classical order differential equations of the given model (1.1) are extended to fractional-order differential equations. This generalization is more effective in capturing the system's dynamics, as fractional derivative operators possess memory effect. On the other hand, integer-order derivatives are inherently local, means does not possess memory effect. Therefore, the fractional differential equations behave more realistic as compared to the integer-order models. Also, there are many fractional derivative operators used in the literature such as Caputo, "Caputo-Fabrizio", Atangana-Baleanu etc., and the most common and widely used operator among them is the Caputo operator. The kernel in the Caputo differential operator decays more gradually than the "exponential kernel" of "Caputo-Fabrizio" and the "Mittag-Leffler kernel" of "Atangana-Baleanu" derivatives. As a result, the Caputo demonstrate stronger and more persistent memory effects than the other two operators. Therefore, the Blood Alcohol model was extended to its fractional form using Caputo fractional operators, as follows:

$$\left. \begin{aligned} {}^C_0 D_t^\alpha S(t) &= -k_1^\alpha S(t) \\ {}^C_0 D_t^\alpha B(t) &= k_1^\alpha S(t) - k_2^\alpha B(t) \end{aligned} \right\} \quad (1.2)$$

with the initial conditions

$$S(0) = S_0, B(0) = B_0 = 0.$$

Table 2. Description of the variables and parameters.

Parameters	Description	Unit
t	Time	minute
α	Order of derivative	nil
$S(t)$	Alcohol concentration in the stomach	mg/l
$B(t)$	Alcohol concentration in the blood	mg/l
k_1	First constant of rate law	nil

k_2	Second constant of rate law	nil
S_0	Initial alcohol concentration in stomach	mg/l
B_0	Initial alcohol concentration in blood	mg/l

Due to the severe impact of alcohol addiction on human life, it becomes a topic of interest for researchers across various disciplines. Previous studies have highlighted the advantages of fractional-order modeling over integer-order approaches in capturing complex dynamics. For instance, a comparison of integer and fractional-order models, including the blood alcohol concentration model, was carried out by Almeida et al. [13], and fractional equations used in their study demonstrated superior accuracy. Jagdev Singh [14] employed the “Sumudu transform” with the “Hilfer fractional operator” to study the blood alcohol model. Qureshi et al. [15] utilized “Caputo”, “CF”, and “ABC” derivatives to study the fractional blood ethanol model, solving it via the Laplace transform. Other works, such as those by Bunoyo and Amadi [16], examined the alcohol’s movement through the gastrointestinal tract, along with its effects on the human body, Prakash et al. [17] employed the Adams-Bashforth method to analyze fractional blood alcohol models using different fractional derivatives. These studies highlight the growing acceptance of fractional-order models as valuable tools for capturing the complex dynamics of alcohol.

In this article, we use a novel iterative technique, the “Modified Adams-Bashforth Moulton method (MABMM)” [18] to address the fractional Blood Alcohol concentration model. The MABMM is a combination of two methods, the “Adams-Bashforth Moulton” method and the “Gejji-Jafari” method. Both these methods are used to solve linear as well as non-linear differential equations. Numerous researchers have effectively employed the Adams-Bashforth-Moulton technique to address fractional differential systems [10,19–21]. Also, the Gejji-Jafari method is utilized by many well-known researchers [22–25]. A variety of fractional derivatives have been introduced in the literature, including “Riemann Liouville”, “Caputo”, “Grünwald-Letnikov” and many more. In this study, we focus on the Caputo fractional derivative to address the current problem. The Caputo derivative has been widely adopted by researchers for solving both linear as well as nonlinear differential equations [26–27].

This paper is divided into several sections as: Section 1 provides the introduction and Section 2 outlines key definitions and theorems utilized throughout the paper. In Section 3, a numerical algorithm is developed to solve the proposed model by using the MABMM. Section 4 presents numerical simulations, visualizes the proposed model’s solution using MATLAB-21, and compares the result with the exact data. At the end, Section 5 summarizes the conclusion.

2. Basic definitions

This section presents the foundational concepts of fractional derivatives and integrals as:

Definition 2.1. The “Caputo fractional derivative of $f(t)$ ” is defined as [1]:

$${}_0^C D_t^\alpha [f(t)] = \frac{1}{\Gamma(m-\alpha)} \int_0^t (t-\tau)^{m-\alpha-1} f^{(m)}(\tau) d\tau,$$

where $m-1 \leq \alpha \leq m, m \in \mathbb{N}$.

Definition 2.2. The “Caputo fractional integration of the function $f(t)$ ”, is given as [1]:

$${}_0^C I_t^\alpha [f(t)] = \frac{1}{\Gamma(\alpha)} \int_0^t (t-\tau)^{\alpha-1} f(\tau) d\tau.$$

Theorem 2.1. "Let $J : \xi \rightarrow \xi$ be a completely continuous operator, and let $D(J) = \{U \in \xi : U = \lambda J(U), \lambda \in [0, 1]\}$ be bounded. Then, there exist at least one fixed point of J in ξ [17]".

Hypothesis (A). "There exists a constant $L > 0$ such that for $U, \overline{U} \in \xi$, we have

$$|F(t, U(t)) - F(t, \overline{U}(t))| \leq L |U(t) - \overline{U}(t)|."$$

Theorem 2.2. [17] "The fractional initial value problem

$${}_0^C D_t^\alpha U(t) = F(t, U(t)),$$

$$U(0) = U_0,$$

with $t \in (0, T)$ has a unique solution if hypothesis (A) is satisfied and

$$\frac{T^\alpha L}{\Gamma(\alpha + 1)} < 1."$$

Lemma 2.1. [17] "The solution for the following perturbed problem

$${}_0^C D_t^\alpha U(t) = F(t, U(t)) + Q(t),$$

$$U(0) = U_0,$$

where $|Q(t)| \leq \epsilon$ for $\epsilon > 0$, satisfies the relation given as:

$$U(t) - \left(U_0 + \frac{1}{\Gamma(\alpha)} \int_0^t F(\tau, U(\tau)) (t - \tau)^{\alpha-1} d\tau \right) \leq \frac{T^\alpha \epsilon}{\Gamma(\alpha + 1)}."$$

Theorem 2.3. [17] "Let us suppose that hypothesis (A) holds. Also, $\frac{T^\alpha L}{\Gamma(\alpha+1)} < 1$. Then the solution of problem (2) is UH stable."

3. Numerical algorithm

This section develops a numerical procedure to solve the proposed model incorporating the Caputo derivative operator, using the Modified Adams-Bashforth-Moulton Method (MABMM). For this, we consider a fractional initial value problem described as follows:

$$\left. \begin{aligned} {}_0^C D_t^\alpha S(t) &= -k_1^\alpha S(t) \\ {}_0^C D_t^\alpha B(t) &= k_1^\alpha S(t) - k_2^\alpha B(t) \end{aligned} \right\} \quad (3.1)$$

initial states:

$$S(0) = S_0, \quad B(0) = B_0 = 0,$$

where $0 < \alpha \leq 1$, and $t \in (0, T)$. To simplify, the right side of the Eq. (3.1) can be expressed as:

$$\left. \begin{aligned} f_1(t, S, B) &= -k_1^\alpha S(t) \\ f_2(t, S, B) &= k_1^\alpha S(t) - k_2^\alpha B(t) \end{aligned} \right\}$$

So, Eq. (3.1) becomes:

$$\left. \begin{aligned} {}_0^C D_t^\alpha S(t) &= f_1(t, S, B) \\ {}_0^C D_t^\alpha B(t) &= f_2(t, S, B) \end{aligned} \right\} \quad (3.2)$$

In vector form, the above equation is written as:

$${}_0^C D_t^\alpha U(t) = F(t, U(t)), \quad (3.3)$$

initial states:

$$U(0) = U_0$$

with

$$U(t) = \begin{bmatrix} S(t) \\ B(t) \end{bmatrix}, \quad U_0 = \begin{bmatrix} S_0 \\ B_0 \end{bmatrix}, \quad F(t, U(t)) = \begin{bmatrix} f_1(t, S, B) \\ f_2(t, S, B) \end{bmatrix}.$$

The Eq. (3.3) is equated to the integral equation as:

$$U(t) = U(0) + \frac{1}{\Gamma(\alpha)} \int_0^t F(\tau, U(\tau))(t - \tau)^{\alpha-1} d\tau, \quad (3.4)$$

The interval $(0, T)$ is divided into N equal parts, with step size $h = \frac{T}{N}$, and points $t_n = nh$, where $n = 0, 1, 2, \dots, N$. Replacing t with t_{n+1} in Eq. (3.4), we get

$$U(t_{n+1}) = U(0) + \frac{1}{\Gamma(\alpha)} \int_0^{t_{n+1}} F(\tau, U(\tau))(t_{n+1} - \tau)^{\alpha-1} d\tau. \quad (3.5)$$

Approximating the above integral yields:

$$U(t_{n+1}) = U(0) + \frac{1}{\Gamma(\alpha)} \sum_{m=0}^n \int_{t_m}^{t_{m+1}} F(\tau, U(\tau))(t_{n+1} - \tau)^{\alpha-1} d\tau. \quad (3.6)$$

Now, by utilizing a two-step Lagrangian polynomial, the function $F(\tau, U(\tau))$ can be approximated as:

$$F(\tau, U(\tau)) = \frac{1}{h} [(\tau - t_m) F(t_{m+1}, U(t_{m+1})) - (\tau - t_{m+1}) F(t_m, U(t_m))]. \quad (3.7)$$

By putting Eq. (3.7) in Eq. (3.6), and solving the integral, we get an implicit expression as follows:

$$\begin{aligned} U(t_{n+1}) = U(0) + \frac{h^\alpha}{\Gamma(\alpha+2)} \sum_{m=0}^n \left[F(t_{m+1}, U(t_{m+1})) \right. \\ \times \left((n-m+1)^{\alpha+1} - (n-m)^\alpha(n-m+1+\alpha) \right) \\ - F(t_m, U(t_m)) \\ \times \left. \left((n-m+1)^\alpha(n-m-\alpha) - (n-m)^{\alpha+1} \right) \right]. \end{aligned} \quad (3.8)$$

The Eq. (3.8) can be simplified as:

$$U(t_{n+1}) = g + N(U), \quad (3.9)$$

where, g is a known function, and $N(U)$ represent the unknown terms of U , given as follows:

$$\begin{aligned} g = U(0) + \frac{h^\alpha}{\Gamma(\alpha+2)} \left[\sum_{m=0}^{n-1} F(t_{m+1}, U(t_{m+1})) \right. \\ \times \left\{ (n+1-m)^{\alpha+1} - (n-m)^\alpha(n-m+1+\alpha) \right\} \\ - \sum_{m=0}^n F(t_m, U(t_m)) \\ \times \left. \left\{ (n+1-m)^\alpha(n-m-\alpha) - (n-m)^{\alpha+1} \right\} \right]. \end{aligned}$$

and

$$N(U) = \frac{h^\alpha}{\Gamma(\alpha+2)} F(t_{i+1}, U(t_{i+1})). \quad (3.10)$$

To solve Eq. (3.9), we apply Gejji-Jafari method [28] which gives solution in the series form as follows:

$$U(t_{n+1}) = U_0 + U_1 + U_2 + \dots = \sum_{j=0}^{\infty} U_j, \quad (3.11)$$

where

$$\left. \begin{aligned} U_0 &= g, \\ U_1 &= N(U_0), \\ U_2 &= N(U_0 + U_1) - N(U_0), \\ &\vdots \\ U_j &= N\left(\sum_{i=0}^{j-1} U_i\right) - N\left(\sum_{i=0}^{j-2} U_i\right), \end{aligned} \right\} \quad (3.12)$$

which is the modified approximate solution of fractional initial value problem (3.3).

4. Results and discussion

This paper analyzes the Caputo fractional blood alcohol model using a hybrid method "MABMM". The numerical solutions for the concentrations of alcohol in the stomach and blood are obtained for different values of the order using the MABMM. The simulations are based on the initial values and parameter, specifically: " $S_0 = 245.8769$, $B_0 = 0$, $k_1 = 0.109456$ and $k_2 = 0.017727$ " [12]. The fractional initial value problem (1.2) is solved numerically with a step size of 0.01, and the outcomes are compared with the exact data.

Figs. 1 and 2 presents the alcohol concentration, at various order of derivatives. These plots indicate how the concentration of alcohol in a human body evolve over time. From the figures, we can observe that the blood alcohol concentration increases initially and then decreases, and in the stomach, the concentration of alcohol decreases with time. It is evident from the simulations that a small change in the fractional order affects the numerical solution. Table 3 indicates significant changes in the concentration of alcohol in the blood as α decreases. Table 4 shows the comparison of Adams Bashforth method and MABMM with the exact solution which clearly indicates that MABMM has higher accuracy at all time steps, demonstrating the accuracy of MABMM. The effectiveness of the technique is also validated through the comparison the outcomes with the exact solution by calculating the "root mean square error (RMSE)", which is obtained as 0.02 in case of ABM and 4.0552×10^{-6} with the MABMM.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (e_i - o_i)^2}{n}} \quad (4.1)$$

where, e_i represent the exact values, o_i represent the calculated values, and n refers to data points. The outcomes revealed that the applied technique is highly effective in solving real-world problems with considerable precision.

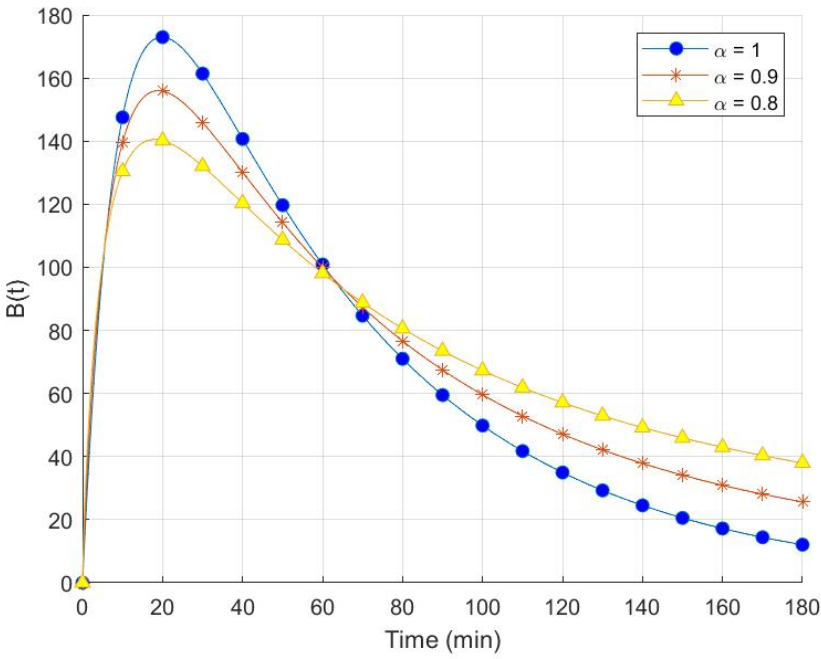


Figure 1: Approximate solution ($B(t)$) for different orders with a step size of $h = 0.01$.

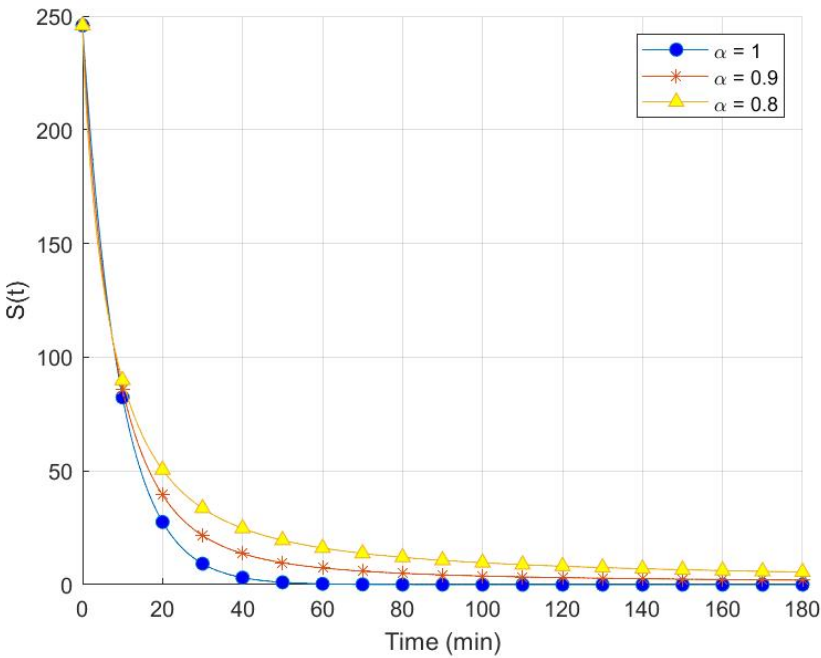


Figure 2: Approximate solution ($S(t)$) for different orders with a step size of $h = 0.01$.

Table 3. Numerical results for concentration of alcohol in blood at different orders.

Time (min)	Exact Solution (mg/l) [12]	MABMM ($\alpha = 1$)	MABMM ($\alpha = 0.9$)	MABMM ($\alpha = 0.8$)
0	0	0	0	0
10	147.54	147.5379	139.4600	130.2636
20	172.95	172.9499	155.6201	139.7251
30	161.38	161.3813	145.7118	131.6391
45	129.99	130.0021	121.9255	114.1443
80	70.99	71.0018	76.6163	80.5145
90	59.49	59.4910	67.4379	73.4330
110	41.74	41.7418	52.8701	61.8479
170	14.41	14.4100	28.1094	40.3585

Table 4. Comparison of the solution obtained via MABMM and ABM for $\alpha = 1$.

Time (min)	Exact Solution (mg/l) [12]	ABM [17]	Absolute error	MABMM	Absolute error
0	0	0	0	0	0
10	147.537897	147.473814	6.41×10^{-2}	147.537907	1×10^{-5}
20	172.949891	172.950335	4.44×10^{-4}	172.949897	6×10^{-6}
30	161.381305	161.399798	1.85×10^{-2}	161.381308	3×10^{-6}
45	130.002091	130.023181	2.11×10^{-2}	130.002092	1×10^{-6}
80	71.001764	71.014311	1.25×10^{-2}	71.001763	1×10^{-6}
90	59.491012	59.501547	1.05×10^{-2}	59.491011	1×10^{-6}
110	41.741823	41.749224	7.40×10^{-3}	41.741823	0
170	14.410036	14.412591	2.56×10^{-3}	14.410036	0

5. Conclusion

This research analyzed the fractional blood alcohol model incorporating Caputo derivative. The proposed model is solved by using a hybrid technique, "MABMM". The results has been compared with those from the classical Adams-Bashforth approach and the exact solution. The comparison is based on the "root mean square error", and observed to be smaller in case of MABMM. This study highlights the potential of the modified technique "MABMM" in solving fractional blood alcohol model, and it is concluded that the modified technique, incorporating the Caputo fractional derivative, is highly effective for modeling real-world problems.

Conflict of interest

All authors declare that this research does not have any conflict of interest.

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Author information

N. Kalyan, Department of Applied Science, University Institute of Engineering and Technology (UIET), Kurukshetra-136119, India.

E-mail: uietphd2025nehakalyan@kuk.ac.in

S. Ahuja, Department of Applied Science, University Institute of Engineering and Technology (UIET), Kurukshetra-136119, Yemen.

E-mail: sahuja2015@kuk.ac.in

A. Prakash, Department of Mathematics, National Institute of Technology, Kurukshetra-136119, India.

E-mail: amitmath@nitkkr.ac.in