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Faculty of Sciences
Department of Mathematics
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Laboratory of Applied Mathematics

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كلية العلوم
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MATHEMATICAL INSIGHTS TO CONTROL EPIDEMICS USING FRACTIONAL OPERATORS

BILAL BASTI AND RABAH DJEMIAT

Abstract. In this paper, we discuss and provide some analytical studies for a mathematical model of fractional-order SIRD for COVID-19 in the sense of the Caputo-Katugampola derivative. We compute and derive several stability results based on some parameters that satisfy some conditions that prevent the pandemic from occurring. The paper also investigates the problem of the existence and uniqueness of solutions for the SIRD model. It does so by applying the properties of Schauder's and Banach's fixed point theorems.

1. Introduction

The coronavirus pandemic was a major worldwide challenge in 2020. The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the virus responsible for COVID-19 infection. Wuhan city in China is reported to be where this virus originated; it then spread throughout the rest of the world, leading to a pandemic outbreak that persisted throughout 2020.

COVID-19 was declared to be a global threat, following its spread outside China as far as we know, and it affected 212 countries around the world. The available antivirals and vaccines at that point in time were ineffective against the new virus, while the new vaccines currently reached the final stage of development and are being tested on larger populations.

A better understanding and evaluation of infectious diseases' existence, stability, and control can be acquired through modeling them mathematically [1, 2]. However, mathematical models' classical approaches are not highly accurate in modeling such diseases; hence, introducing fractional differential equations for handling these problems becomes necessary. We mention optimization problems, artificial intelligence, medical diagnoses, and their various applications in applied fields. For further reading on the subject, readers can refer to the following books (Samko *et al.* 1993 [3], Podlubny 1999 [4], Kilbas *et al.* 2006 [5], Diethelm 2010 [6]).

Our model requires the division of the total population $\mathcal{N}$ into four epidemiological classes:

$$\mathfrak{S} : \text{Susceptible class, } \mathfrak{I} : \text{Infected class, } \mathfrak{R} : \text{Recovered class, and } \mathfrak{D} : \text{Death class.}$$

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The parameters are positive and could be described as follows:

- ∘ β is the average number of contacts per person per time t,
- ∘ γ is the recovery rate,
- ∘ κ is the death rate.

For $0<\alpha<1$ and $\rho>0$,

$$\left\{\begin{array}{lcl} {}^{C}\mathcal{D}_{0^{+}}^{\alpha;\rho}\mathfrak{S}\left(t\right) & = & -\beta\frac{\mathfrak{S}(t)\mathfrak{I}(t)}{\mathcal{N}_{0}}, \\ {}^{C}\mathcal{D}_{0^{+}}^{\alpha;\rho}\mathfrak{I}\left(t\right) & = & \beta\frac{\mathfrak{I}(t)\mathfrak{S}(t)}{\mathcal{N}_{0}}-\left(\gamma+\kappa\right)\mathfrak{I}\left(t\right), \\ {}^{C}\mathcal{D}_{0^{+}}^{\alpha;\rho}\mathfrak{R}\left(t\right) & = & \gamma\mathfrak{I}\left(t\right), \\ {}^{C}\mathcal{D}_{0^{+}}^{\alpha;\rho}\mathfrak{D}\left(t\right) & = & \kappa\mathfrak{I}\left(t\right), \end{array}\right. \tag{1.1}$$

along with the positive initial conditions

$$\mathfrak{S}\left(0\right)=\mathfrak{S}_{0},\ \mathfrak{I}\left(0\right)=\mathfrak{I}_{0},\ \mathfrak{R}\left(0\right)=\mathfrak{R}_{0},\ \mathfrak{D}\left(0\right)=\mathfrak{D}_{0}, \tag{1.2}$$

where $\mathcal{N}_0>0$ is the initial total population at the moment $t=0$, with $0\leq t\leq T<\infty$.

It is essential to find the solution of (1.1) with an efficient technique. Considering this point, our main goal in this work is to determine the main properties of the solution for the system of nonlinear fractional differential equations (1.1), checking the considered model's stability necessitates establishing some existence results.

2. Preliminary and necessary definitions

The essential definitions from the fractional calculus theory are introduced in this section. Banach space of continuous functions from $[0,T]$ into $\mathbb{R}$ is denoted by $C\left(\left[0,T\right],\mathbb{R}\right)$, with the norm:

$$\left\Vert\varphi\right\Vert_{\infty}=\sup_{t\in[0,T]}\left\vert\varphi\left(t\right)\right\vert.$$

Recently, Katugampola proposed a generalized derivative in [7, 8, 9, 10]; moreover, he demonstrated the existence of solutions of Caputo-Katugampola fractional differential equations in [9]. It reads

$${}^{C}\mathcal{D}_{0^{+}}^{\alpha;\rho}\varphi\left(t\right)=\mathcal{I}_{0^{+}}^{1-\alpha,\rho}\left(\tau^{1-\rho}\frac{d}{d\tau}\varphi\right)\left(t\right)=\frac{\rho^{\alpha}}{\Gamma\left(1-\alpha\right)}\int_{0}^{t}\frac{\varphi'\left(\tau\right)}{\left(t^{\rho}-\tau^{\rho}\right)^{\alpha}}d\tau, \tag{2.1}$$

where $\alpha\in\left(0,1\right)$, $\rho>0$ and

$$\mathcal{I}_{0^{+}}^{\alpha,\rho}\varphi\left(t\right)=\frac{\rho^{1-\alpha}}{\Gamma\left(\alpha\right)}\int_{0}^{t}\frac{\tau^{\rho-1}}{\left(t^{\rho}-\tau^{\rho}\right)^{1-\alpha}}\varphi\left(\tau\right)d\tau,\ \text{with } \varphi\in C\left(\left[0,T\right],\mathbb{R}\right). \tag{2.2}$$

At this point, it is worth mentioning that a fractional Cauchy-type problem was solved for an existence and uniqueness theorem in [11], a decomposition formula for the derivative of Caputo-Katugampola among others could, thus, be obtained as follows:

$$\mathcal{I}_{0^{+}}^{\alpha,\rho}\ {}^{C}\mathcal{D}_{0^{+}}^{\alpha,\rho}\varphi\left(t\right)=\varphi\left(t\right)-\varphi\left(0\right),\ \text{for } \varphi\in C\left(\left[0,T\right],\mathbb{R}\right). \tag{2.3}$$

It follows from (2.1) that if $\rho=1$, Caputo-Katugampola derivative is found to be the well-known Caputo fractional derivative [4, 5]. On the other hand, by applying the L'Hôspital rule, when $\rho \to 0^+$, we have

$$\begin{aligned}\lim_{\rho\to 0^+} \frac{\rho^\alpha}{\Gamma(1-\alpha)} \int_0^t \frac{\varphi'(\tau)}{(t^\rho - \tau^\rho)^\alpha} d\tau &= \frac{1}{\Gamma(1-\alpha)} \int_0^t \lim_{\rho\to 0^+} \frac{\rho^\alpha \varphi'(\tau)}{(t^\rho - \tau^\rho)^\alpha} d\tau \\ &= \frac{1}{\Gamma(1-\alpha)} \int_0^t \frac{\varphi'(\tau)}{(\ln t - \ln s)^\alpha} d\tau,\end{aligned}$$

which is Caputo-Hadamard fractional derivative [12, 10, 8].

3. Main Results

Lemma 3.1. *The solution of model (1.1) is restricted to the feasible region given by*

$$u = \left\{ (\mathfrak{S}, \mathfrak{I}, \mathfrak{R}, \mathfrak{D}) \in \mathbb{R}_+^4,\ 0 \le \mathcal{N}(t) \le \mathcal{N}_0 \right\},$$

and the pandemic will occur if $\mathfrak{S}_0 > \frac{\gamma+\kappa}{\beta}\mathcal{N}_0$, *where* $\frac{\gamma+\kappa}{\beta}$ *is called threshold phenomenon or critical community size for the pandemic.*

Theorem 3.2. *The disease-free equilibrium point of (1.1) is*

$$u^* = \left(\frac{\gamma+\kappa}{\beta}\mathcal{N}_0, 0, \mathfrak{R}_0, 0 \right).$$

Theorem 3.3. *If the susceptible class* $\mathfrak{S}(t) < \mathfrak{S}^*$, *the pandemic free equilibrium point of (1.1) is locally asymptotically stable and is unstable if* $\mathfrak{S}(t) > \mathfrak{S}^*$.

Let $u = (\mathfrak{S}, \mathfrak{I}, \mathfrak{R}, \mathfrak{D}) \in E$, where $E = [C([0,T], \mathbb{R}_+)]^4$ is a Banach space equipped with the norm

$$\|u\|_E = \|\mathfrak{S}\|_\infty + \|\mathfrak{I}\|_\infty + \|\mathfrak{R}\|_\infty + \|\mathfrak{D}\|_\infty$$

and let $f = (f_1, f_2, f_3, f_4)$, be such that

$$\left\{ \begin{array}{lll} f_1(t, u(t)) &=& -\beta \frac{\mathfrak{S}(t)\mathfrak{I}(t)}{\mathcal{N}_0}, \\ f_2(t, u(t)) &=& \beta \frac{\mathfrak{I}(t)\mathfrak{S}(t)}{\mathcal{N}_0} - (\gamma+\kappa)\mathfrak{I}(t), \\ f_3(t, u(t)) &=& \gamma \mathfrak{I}(t), \\ f_4(t, u(t)) &=& \kappa \mathfrak{I}(t), \end{array} \right.$$

it is clear that the function $f \in ([0,T] \times E)^4$ is continuous.

By applying the fractional integral to both sides of the system (1.1), we get

$$\left\{ \begin{array}{lll} \mathfrak{S}(t) &=& \mathfrak{S}_0 + \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_0^t \frac{\tau^{\rho-1}}{(t^\rho-\tau^\rho)^{1-\alpha}} f_1(\tau, u(\tau))\, d\tau, \\ \mathfrak{I}(t) &=& \mathfrak{I}_0 + \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_0^t \frac{\tau^{\rho-1}}{(t^\rho-\tau^\rho)^{1-\alpha}} f_2(\tau, u(\tau))\, d\tau, \\ \mathfrak{R}(t) &=& \mathfrak{R}_0 + \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_0^t \frac{\tau^{\rho-1}}{(t^\rho-\tau^\rho)^{1-\alpha}} f_3(\tau, u(\tau))\, d\tau, \\ \mathfrak{D}(t) &=& \mathfrak{D}_0 + \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_0^t \frac{\tau^{\rho-1}}{(t^\rho-\tau^\rho)^{1-\alpha}} f_4(\tau, u(\tau))\, d\tau, \end{array} \right.$$

By choosing $u_0 = (u_1, u_2, u_3, u_4) = (\mathfrak{S}_0, \mathfrak{I}_0, \mathfrak{R}_0, \mathfrak{D}_0)$, we get

$$u(t) = u_0 + \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_0^t \frac{\tau^{\rho-1}}{(t^\rho - \tau^\rho)^{1-\alpha}} f(\tau, u(\tau))\, d\tau. \tag{3.1}$$

In what follows, we present the principal theorems:

Theorem 3.4. *Let $\beta, \gamma, \kappa, \alpha, \rho, T \in \mathbb{R}_+$, be such that $\alpha \in (0,1)$ and*

$$T < \left(\frac{\rho^{\alpha} \Gamma(\alpha+1)}{4(\beta+\gamma+\kappa+3)} \right)^{\frac{1}{\rho\alpha}}, \tag{3.2}$$

then the problem (1.1)–(1.2) has at least one solution on $[0,T]$.

Theorem 3.5. *Let $\alpha \in (0,1)$ and $\beta, \gamma, \kappa, \rho, \mu \in \mathbb{R}_+^*$, be such that*

$$\mu = \max\{\beta+\gamma+\kappa+2, \gamma+3, \kappa+3\}.$$

If

$$\frac{4\mu T^{\rho\alpha}}{\rho^{\alpha}\Gamma(\alpha+1)} < 1, \tag{3.3}$$

then the problem (1.1)–(1.2) admits a unique solution on $[0,T]$.

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INTERNATIONAL CONFERENCE ON MATHEMATICS AND ITS APPLICATIONS IN SCIENCE AND TECHNOLOGY

ICMAST' 2024

Setif, December 15-16, 2024

Auditorium : Mouloud Kacem Nait Belkacem- El Bez

CONFERENCE PROGRAM

Sunday, December 15th, 2024 - Morning	
8h 00 – 9h 00	**WELCOME - REGISTRATION**
9h 00 – 9h 30	**OPENING CEREMONY**
9h 30 – 10h 30	Chairman: **Pr. Bachir YALAOUI** Speaker : **Pr. Abdellah SALHI** - Title ‘’ **Strawberry Plants will get you there: Plant Propagation-based Optimization** ‘’
10h 30 – 11h 00	***COFFEE BREAK***
11h 00 – 12h 00	Chairman : **Pr. Abdellah SALHI** Speaker : **Pr. Haslinda IBRAHIM** – Title: ‘’ **Explore, Discover & Develop (ExDID): A Combinatorial Path to Problem Solving and Nature-Inspired Design** ‘’

	POSTER SESSION		
10h 00 – 12h 00	• Moufida Goutali • Nor Sahnoune • Bochra Zeghad • Nassima Anane • Hadjer Laraba • Choubeila Souli • Raouf Ziadi	• Rania Benmenni • Nour el islam Hiber • Djaouida Guettal • Asma Maiza • Barkahoum Chebabhi • Amel Noui • Ahmed Ayoub Boukelia	• Aicha Kraria • Merzaka Khaldi • Assma Leulmi • Soumaya Belabbes • Fatima Khanchouche • Baya Takhedmit • Razika Sait

12h 00 – 14h 00	***LUNCH BREAK***

Sunday, December 15th, 2024 – Afternoon			
	ORAL SESSION		
	SESSION 1: Differential Equations and its Applications **Chairman :** H. Benseridi	**SESSION 2:** Dynamic Systems and Mathematical Biology **Chairman :** S. Mesbahi	**SESSION 3:** Algebra, Cryptography and Information Security **Chairman :** N. Trabelsi
14h 00 – 14h 20	**Sara Hadi** Some results on the asymptotic behaviour of Allen-Cahn equation	**Bilel Elbetch** Effect of nonlinear diffusion and spatial heterogeneity on the dynamics of a population and on the coexistence of species	**Zineb Hebbache** On negacyclic codes over mixed alphabet $\mathbb{Z}_p(\mathbb{Z}_p + v\mathbb{Z}_p)$
14h 20 – 14h 40	**Hamza Brahim Boulares** Maximal, Calderon-Zygmund and sublinear operators on variable weak Herz spaces	**Mohamed Cherif Benkara Mostefa** Study of a differential-algebraic system with harvesting prey	**Ahlem Hamani** Some results on minimal non-finite-by-(locally nilpotent) groups
14h 40 – 15h 00	**Houd Khireddine** On a dynamic frictional contact problem with tresca’s friction	**Nesrine Benmehenni** Enhancing watermark security through Hénon-based digit shuffling	**Zoulikha Benhelal** Groups whose proper subgroups of infinite rank are (locally finite)-by-engel
15h 00 – 15h 20	**Imed Heddar** Stability via Lyapunov pairs for nonlinear differential equations	**Yassine Adjabi** Lyapunov and Hartman type inequalities for a class of mixed nonlinear generalized Caputo fractional differential equations with a forcing term	**Boualem Sadaoui** A general recursion formula for the multiple Hurwitz zeta values at non positive integers
15h 20 – 15h 50	**COFFEE BREAK**		
	SESSION 1: Differential Equations and its Applications **Chairman :** S. Boutechebak	**SESSION 2:** Numerical Analysis and Simulation **Chairman :** Dj. Benterki	**SESSION 3:** Mathematical Finance and Economics **Chairman :** N. Daili
15h 50 – 16h 10	**Bilel Madjour** General decay of solutions for a von Karman plate equations with nonlinear fractional damping	**Bachir Merikhi** Inverse barrier method for nonlinear programming	**Amel Belhadj** An extension of rough volatility model in financial markets
16h 10 – 16h 30	**Amirouche Laadjel** Some perov fixed points results in generalized tow metric spaces	**Nawel Boudjellal** A theoretical and numerical study of a new weighted interior point method based on algebraic equivalent transformation for LCCO	**Amira Rami** Stabilization of fractional order duopoly game between an heterogeneous player and boundedly rational player with adaptive expectation
16h 30 – 16h 50	**Lamia Chouchane** Variational analysis of an elecro-viscoelastic contact problem with normal compliance and unilateral constraint	**Mostafa Bahi** Study the uniform convergence of multigrid methods for parabolic variational inequality noncoercive	**Aicha Ghanem** Parametric curves in Isaac’s pursuit-evasion game

14h 30– 16h 30	***POSTER SESSION***		
	• Chamseddine Bouaziz • Abdelmounaim Hamdi • Samiha Djemai • Houssem Eddine Kadem • Safa Benghebrid • Mohamed Meziani • Nedjma Boulelli	• Bachir Fridjat • Karima Laidoune • Bilal Basti • Lina Chetioui • Fatima Hathat • Roufaida Ketfi • Meriem Guechi	• Imane Zouak • Riadh Hedli • Tarek Rouabhi • Fatiha Barache • Leila Younsi née Abbaci • Lamia Djerroud • Zina Hamoudi

Monday, December 16th, 2024 – Morning

08h 30 – 09h 30	Chairman : **Pr. Aissa AIBECH** Speaker : **Pr. Abderrahmene ZIAD** - Title ‘’ **Strong Nash implementation in finite and infinite fair allocation problems** ‘’		
9h 30 – 10h 30	Chairman: **Pr. Abderrahmene ZIAD** Speaker : **Pr. Said Houari Belkacem** - Title ‘’ **Reaction diffusion systems and applications** ‘’		
10h 30 – 11h 00	***COFFEE BREAK***		
	ORAL SESSION		
	SESSION 1: Differential Equations and its Applications **Chairman :** I. Boukaroura	**SESSION 2:** Data Science and Analytics **Chairman :** Y. Bencheikh	**SESSION 3:** Algebra, Cryptography and Information Security **Chairman :** T. Rouabhi
11h 00 – 11h 20	**Soumia Hamdi** Well-posedness and stability result for a flexible satellite system under unknown distributed disturbances during attitude maneuvering	**Fella Berrimi** Mathematical tools for image processing and artificial intelligence	**Kheir Saadaoui** On intuitionistic and neutrosophic fuzzy sets
11h 20 – 11h 40	**Dalila Bitat** Some generalizations of integral inequalities of wendroff type	**Ikram Bouras** Path based formulation for the maximum influence problem in signed social networks	**Raouda Chettouh** The intersection of the disk and the rectangle containing the numerical range of a bounded linear operator
11h 40 – 12h 00	**Ghada Boutara** A modified quasi-boundary value method for a class of inverse problem with involution	**Massilva Bourouina** Nonparametric reliability estimation with three families of asymmetric kernels	**Salah Eddine Rihane** Complete solutions of the exponential Diophantine equation $P_n^x + P_{n+1}^x = P_m^y$
	POSTER SESSION		
10h 00 – 12h 00	• Abbes Ourahmoun • Samira Zahar • Abla Boulaouad • Sihem Smata • Hamid Achab • Rim Benzatat • Khaoula imane Saffidine	• Besma Founas • Sabrina Guidoum • Narimene Achour • Abdelaaziz Bouziane • Meriem Chabekh • Imane Boudrissa • Imane Aouina	• Slimane Hassaine • Fouzia Bouzeghaya • Chaima Benarab • Yasmina Kadri • Taklit Hana Lahlah • Aziza Aib
12h 00 – 14h 00	***LUNCH BREAK***		

Monday, December 16th, 2024 – Afternoon

	ORAL SESSION		
	SESSION 1: Numerical Analysis and Simulation + Algebra, Cryptography and information Security **Chairman :** N. Chougui	**SESSION 2:** Numerical Analysis and Simulation **Chairman :** M. Achache	**SESSION 3:** Fractional Calculus + Mathematical Methods in Engineering + History of science **Chairman :** A. Kadem
14h 00 – 14h 20	**Amel Dilmi** Groups whose proper subgroups of infinite rank are finite-by-hypercentral or hypercentral-by-finite	**Allaoua Mehri** *A new error estimation of a finite difference Scheme for a transport-advection equation with fractional order derivative*	**Mongia Khlifi** On the Super Catalan numbers and their applications
14h 20 – 14h 40	**Raouf Bouchelaghem** On the linear independence measures of logarithms of rational numbers. ii	**Youcef Elhamam Hemici** Study of a modified PRP method using a diagonal hessian approximation approach	**Abdelhadi Safsaf** Well posedness of coupled nonlinear wave equations with logarithmic source terms and blow-up
14h 40 – 15h 00	**Welid Grimes** Polynomial interior-point algorithms for linearly constrained convex optimization	**Mohamed Lamine Ouaoua** Comparative numerical study between differents variants of conjugate gradient methods of the Dai-Liao type	**Kheireddine Boudehane** A markov regenerative stochastic petri net for performance and reliability analysis of a 3-out-of-(2+2+1):G repairable redundant system
15h 00 – 15h 20		**Yasmina Bendaas** A numerical study of an infeasible interior-point algorithm for convex quadratic semi-definite optimization	**Brahim Moussaouali** The critical analysis of Euclidean geometry in the arab tradition
15h 20 – 15h 50	**COFFEE BREAK**		
15h 50 – 16h 20	**CLOSING CEREMONY**		