## Implicit Fractional Differential Equations in Banach Spaces via Picard and Weakly Picard Operator Theory

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#### Abstract

In this paper, by employing fixed-point methods, we obtain the existence and uniqueness results for the nonlinear implicit fractional differential equations in Banach spaces. Further, we obtain the uniqueness, dependence of the solution on the initial condition as well as on the functions involved on the right-hand side by means of Picard and weakly Picard operator theory and Pompeiu–Hausdorff functional.

Key words: Implicit fractional differential equations, existence, uniqueness, continuous dependence, Picard opeartors, Weakly Picard operators.
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## 1 Introduction

The initial and boundary value problems for fractional differential equations (FDEs) are naturally appearing in the modeling of various physical phenomena that appearing in diverse disciplines of science and engineering [1, 2, 3, 4, 5, 6]. Subsequently, this field is drawing the attention of many mathematicians for researching numerous types of FDEs for its theory and applicability. Basics of fractional calculus, detailed theoretical analysis and applications of FDEs can be found in the interesting monographs by Kilbas et al.[7], Lakshmikantham et al. [8], Podlubny [9], Diethelm [10]. Fundamental results on the existence and uniqueness of solutions, comparison results, different types of data dependency, the existence of extremal solutions and global existence of the nonlinear FDEs can found in [11, 12, 13, 14, 15, 16, 17]. Recently, there have been numerous papers that deal with the existence, uniqueness, controllability and various qualitative properties of the solution for FDEs with initial and boundary conditions [18, 19, 20, 21].

The implicit differential equation of the form

$$x^{(n)}(t) = f\left(t, x(t), x'(t), x''(t), \cdots, x^{(n-1)}(t)\right),$$

with different kind of initial or boundary condition has been analyzed for existence, uniqueness and various other qualitative properties of the solution, for instance, see [22] and the references cited therein. Motivated by the investigations in the theory of integer order implicit differential equation considered above and its different special from, Benchohra et al. [23, 24] and Nieto et al. [25] have initiated the study of implicit FDEs of the form

$$D^{\alpha}x(t) = f(t, x(t), D^{\alpha}x(t)),$$

with a different kind of initial and boundary condition. Nieto et al. [25] derived existence and uniqueness results by employing fixed point theory and an approximation method. Benchohra et al. [26, 27, 28] investigated the existence of integrable solutions for implicit fractional functional differential equations with and without delay. Kucche et.al. in [30, 31, 32] have analyzed implicit FDEs for existence, uniqueness dependence of solution on various initial data and Ulam–Hyers and Ulam–Hyers-Rassias stabilities.

On the other hand, Rus [33, 34] introduced the fundamental results of the weakly Picard operators theory and employed it to analyze the Cauchy problem, boundary value problem, integral equations, and difference equations. Wang [35] obtained some existence, uniqueness, and data dependence results by means of Picard and weakly Picard operators theory and the Bielecki norms. Then again, Otrocol and Ilea [36, 37] analyzed differential and integrodifferential equations with abstract Volterra operators using the method of Picard and weakly Picard operators.

Motivated by the work of [34, 35], in the present manuscript, we obtain the existence, uniqueness and dependency of solution for the nonlinear implicit FDEs of the form,

$${}_{0}^{c}\mathcal{D}_{t}^{\alpha}x(t) = f\left(t, x(t), {}_{0}^{c}\mathcal{D}_{t}^{\alpha}x(t)\right), t \in J, \ 0 < \alpha < 1$$
(1.1)

$$x(0) = x_0 \in X,\tag{1.2}$$

in the Banach space  $X = (X, \|\cdot\|)$ , where J = [0, T], T > 0,  ${}_{0}^{c}\mathcal{D}_{t}^{\alpha}$  is the Caputo fractional derivative operator of order  $\alpha$  and lower terminal 0 and  $f : J \times X \times X \to X$  is a nonlinear function satisfying certain assumptions.

We obtain the existence and uniqueness of the solution by using fixed-point methods in the space of Lipschitz function and considering the Bielecki norm. The dependency of a solution is obtained through Picard operator theory and Pompeiu–Hausdorff functional. It is observed that the single inequality obtained for the difference of solutions via Picard operator theory gives simultaneously, the uniqueness of solution, the dependence of the solution on the initial condition as well as on the functions involved on the right-hand side of the problem (3.14)-(3.15). Whereas, the inequality obtained for the solutions via Pompeiu–Hausdorff functional gives the dependency of the solution on functions involved in the right hand side of the problem (3.14)-(3.15).

This paper is structured in the following way. In section 2, we present briefly the basic definitions and results of fractional calculus, Picard and weakly Picard operators. In Section 3, we obtain the existence, uniqueness and dependency of solution for the nonlinear implicit FDEs (3.14)-(3.15). In Section 4, we provide examples to illustrate our results. Finally,we close the paper with concluding remarks.

## 2 Preliminaries

In this section, we give some definitions and basic results of Caputo fractional derivative [10, 9] and Picard and weakly Picard operator theory [33, 35, 38].

**Definition 2.1** The Riemann-Liouville fractional integral  $\mathcal{I}_{0,t}^{\beta}$  of order  $\beta > 0$  of a function  $g \in C[0,T], T > 0$  is defined as

$$\mathcal{I}^{\beta}_{0,t} g(t) = \frac{1}{\Gamma(\beta)} \int_0^t (t-\sigma)^{\beta-1} g(\sigma) d\sigma, \quad t > 0,$$

provided the integral exists.

**Definition 2.2** Let  $0 < \alpha \leq 1$  then the Caputo fractional derivative  ${}_{0}^{c}\mathcal{D}_{t}^{\alpha}$  of order  $\alpha$  with lower terminal 0 of a function  $g \in C^{1}[0,T]$  is defined as

$${}_0^c \mathcal{D}_t^{\alpha} g(t) = \frac{1}{\Gamma(1-\alpha)} \int_0^t (t-\sigma)^{-\alpha} g'(\sigma) d\sigma, \ t > 0.$$

Next, we provide the basics of Picard and weakly Picard operators theory from [33, 35, 38]. Let X := (X, d) be a metric space and  $T : X \to X$  an operator. Then:

- (i)  $P(X) := \{Y \subseteq X : Y \neq \phi\}.$
- (ii)  $F_T := \{x \in X : T(x) = x\}$  the fixed point set of T.
- (iii)  $I(T) := \{Y \in P(X) : T(Y) \subseteq Y\}$  a set of T-invariant nonempty subsets X.

(iv) The Pompeiu-Hausdorff functional  $H_d: P(X) \times P(X) \to \mathbb{R}_+ \cup \{\infty\}$  is defined as

$$H_d(Y,Z) = \max\left\{\sup_{a\in Y} \inf_{b\in Z} d(a,b), \sup_{b\in Z} \inf_{a\in Y} d(a,b)\right\}.$$

**Definition 2.3 ([35])** Let (X, d) be a metric space. An operator  $T : X \to X$  is a Picard operator if there exists  $x^* \in X$  such that  $F_T = \{x^*\}$  and the sequence  $(T^n(x_0))_{n \in \mathbb{N}}$  converges to  $x^*$  for all  $x_0 \in X$ .

**Definition 2.4 ([35])** Let (X,d) be a metric space. An operator  $T : X \to X$  is a weakly Picard operator if the sequence  $(T^n(x_0))_{n \in \mathbb{N}}$  converges for all  $x_0 \in X$  and its limit ( which may depend on  $x_0$  ) is a fixed point of T.

If  $T: X \to X$  is a weakly Picard operator, then the operator  $T^{\infty}: X \to X$  defined by

$$T^{\infty}(x) = \lim_{n \to \infty} T^n(x).$$

**Lemma 2.1 ([35])** Let (X, d) be a metric space. Then  $T : X \to X$  is a weakly Picard operator if and only if there exists a partition of X,  $X = \bigcup_{\lambda \in \Lambda} X_{\lambda}$ , where  $\Lambda$  is the indices' set of partition, such that

- (i)  $X_{\lambda} \in I(T)$ ,
- (ii)  $T|_{X_{\lambda}}: X_{\lambda} \to X_{\lambda}$  is a Picard operator, for all  $\lambda \in \Lambda$

**Lemma 2.2 ([35])** Let (X, d) be a complete metric space and  $T, S : X \to X$  two operators. We suppose the following

- (i) T is a contraction with constant  $\alpha$  and  $F_T = \{x_T^*\}$ .
- (ii) S has a fixed points and  $x_S^* \in F_S$ .
- (iii) There exists  $\gamma > 0$  such that  $d(T(x), S(x)) \leq \gamma$ , for all  $x \in X$ .

Then,

$$d\left(x_{T}^{*}, x_{S}^{*}\right) \leq \frac{\gamma}{1 - \alpha}$$

**Lemma 2.3 ([35])** Let (X, d) be a complete metric space and  $T, S : X \to X$  two orbitally continuous operators. We suppose the following:

(i) There exists  $\alpha \in [0, 1)$  such that

$$d\left(T^{2}(x), T(x)\right) \leq \alpha \ d\left(T(x), x\right)$$
$$d\left(S^{2}(x), S(x)\right) \leq \alpha \ d\left(S(x), x\right)$$

for all  $x \in X$ .

(ii) There exists  $\gamma > 0$  such that  $d(T(x), S(x)) \leq \gamma$ , for all  $x \in X$ .

Then,

$$H_d(F_T, F_S) \le \frac{\gamma}{1-\alpha}$$

where  $H_d$  denotes Pompeiu-Hausdorff functional.

## 3 Main results

To derive our main results, we consider the spaces defined in [35].

Let C := C(J, X) be the space of all X-valued continuous functions defined on J. Then  $\mathcal{C} := (C, \|\cdot\|_{\mathcal{C}})$  is the Banach space with the Chebyshev norm

$$||x||_{\mathcal{C}} := \sup_{t \in J} \{||x(t)||\}.$$

Further,  $\mathcal{B} = (C, \|\cdot\|_B)$  is the Banach space endowed with the Bielecki norm

$$||x||_B := \sup_{t \in J} \left\{ \frac{||x(t)||}{\mathbb{E}_{\alpha} \left( \theta t^{\alpha} \right)} \right\}, \ x \in C \text{ for some } \theta > 0.$$

Let  $d_{\mathcal{B}}$  and  $d_{\mathcal{C}}$  are the metrics on C generated by the norms  $\|\cdot\|_{\mathcal{B}}$  and  $\|\cdot\|_{\mathcal{C}}$ .

Let L > 0 and define the set

$$C_L(J,X) := \{ x \in C(J,X) : ||x(t_1) - x(t_2)|| \le L|t_1 - t_2|, \ \forall \ t_1, \ t_2 \in J \}.$$

Let R > 0,  $B_R = S[0, R] = \{x \in X : ||x|| \le R\}$  and

$$C_L(J, B_R) := \{ x \in C(J, B_R) : ||x(t_1) - x(t_2)|| \le L|t_1 - t_2|, \ \forall \ t_1, t_2 \in J \}.$$

We acquire our main results via equivalent fractional integral equation to the nonlinear implicit FDEs (1.1)–(1.2) given in the following lemma.

**Lemma 3.1 ([26])** The solution of the IVP (1.1)–(1.2) can be expressed by the integral equation

$$x(t) = x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, \ t \in J;$$
(3.1)

where z is the solution of the functional integral equation

$$z(t) = f\left(t, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), t \in J.$$
(3.2)

### 3.1 Existence and Uniqueness Results:

**Theorem 3.2** Assume that:

(A1)  $f: J \times X \times X \to X$  is a continuous function and satisfies Lipschitz type condition

$$\|f(t_1, x_1, y_1) - f(t_2, x_2, y_2)\| \le M_1 |t_1 - t_2| + M_2 \|x_1 - x_2\| + M_3 \|y_1 - y_2\|, \quad (3.3)$$

for all  $t_i \in J$  and  $x_i, y_i \in X$ , where  $M_i > 0$ , i = 1, 2 and  $0 < M_3 < 1$ .

Then, the problem (1.1)–(1.2) has unique solution, provided that

$$\frac{M_2}{\Gamma(\alpha+1)}T^{\alpha} + M_3 < 1. \tag{3.4}$$

Further, the solution  $z^* \in C_L(J, B_R)$  of functional integral equation (3.2) can be obtained by successive approximation method starting from any element of  $C_L(J, B_R)$ . Utilizing this  $z^*$ , the solution  $x^*$  of (1.1)–(1.2) is then acquired from the equation (3.1). *Proof:* In the view of condition (3.4), we can choose R > 0 such that

$$\frac{M_2 \|x_0\| + K}{1 - \left(\frac{M_2}{\Gamma(\alpha + 1)}T^{\alpha} + M_3\right)} \le R,$$
(3.5)

where  $K = \sup_{t \in J} ||f(t, 0, 0)||$ . Further the condition  $0 < M_3 < 1$  allows us to choose L > 0 such that

$$\frac{M_1 + \frac{2M_2R}{\Gamma(\alpha+1)}}{1 - M_3} \le L.$$
(3.6)

With these choices of L and R consider the space

$$C_L(J, B_R) := \{ x \in C(J, B_R) : ||x(t_1) - x(t_2)|| \le L|t_1 - t_2|, \ \forall \ t_1, t_2 \in J \}.$$

Define the mapping,

$$(Tz)(t) = f\left(t, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), \ t \in J, \ z \in C_L(J, B_R),$$
(3.7)

We show that the operator T is a Picard operator on  $C_L(J, B_R)$ . We divide the proof in the two parts.

Part-(I): First we prove that T is self map on  $C_L(J, B_R)$ . We give the proof in the following steps.

Step 1:  $Tz \in C(J, X)$  for any  $z \in C_L(J, B_R)$ .

Let any  $\delta > 0$ . Then for any  $z \in C_L(J, B_R)$  and  $t \in J$ , we have

$$||z(t+\delta) - z(t)|| \le L|t+\delta-t| = L\delta, \text{ and } ||z(t)|| \le R.$$
 (3.8)

By Lipschitz type condition on f given in (A1) and using the inequalities in (3.8), we obtain

$$\begin{split} \| (Tz)(t+\delta) - (Tz)(t) \| \\ &= \left\| f \left( t + \delta, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^{t+\delta} (t+\delta-s)^{\alpha-1} z(s) ds, z(t+\delta) \right) \\ &- f \left( t, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t) \right) \right\| \\ &\leq M_1 | (t+\delta) - t | + M_2 \left\| \left( x_0 + \frac{1}{\Gamma(\alpha)} \int_0^{t+\delta} (t+\delta-s)^{\alpha-1} z(s) ds \right) \\ &- \left( x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds \right) \right\| + M_3 \| z(t+\delta) - z(t) \| \\ &\leq M_1 \delta + \frac{M_2}{\Gamma(\alpha)} \int_0^t \left[ (t+\delta-s)^{\alpha-1} - (t-s)^{\alpha-1} \right] \| z(s) \| ds \\ &+ \frac{M_2}{\Gamma(\alpha)} \int_t^{t+\delta} (t+\delta-s)^{\alpha-1} \| z(s) \| ds + M_3 \| z(t+\delta) - z(t) \| \\ &\leq (M_1 + M_3 L) \delta + \frac{M_2 R}{\Gamma(\alpha)} \int_0^t \left[ (t+\delta-s)^{\alpha-1} - (t-s)^{\alpha-1} \right] ds + \frac{M_2 R}{\Gamma(\alpha)} \int_t^{t+\delta} (t+\delta-s)^{\alpha-1} ds \end{split}$$

$$= (M_1 + M_3 L)\delta + \frac{M_2 R}{\Gamma(\alpha + 1)} \left\{ \left[ -\delta^{\alpha} + (t + \delta)^{\alpha} - t^{\alpha} \right] + \delta^{\alpha} \right\}$$
$$= (M_1 + M_3 L)\delta + \frac{M_2 R}{\Gamma(\alpha + 1)} \left[ (t + \delta)^{\alpha} - t^{\alpha} \right].$$

Therefore,

$$\lim_{\delta \to 0} \| (Tz)(t+\delta) - (Tz)(t) \| = 0.$$

This proves that  $Tz \in C(J, X)$ .

Step 2:  $Tz \in C_L(J, B_R)$  for any  $z \in C_L(J, B_R)$ . Let any  $z \in C_L(J, B_R)$ . Then using inequalities (3.5) and (3.8), for any  $t \in J$ , we obtain

$$\begin{split} \|T(z)(t)\| &= \left\| f\left(t, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right) \right\| \\ &= \left\| f\left(t, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right) - f\left(t, 0, 0\right) \right\| + \|f\left(t, 0, 0\right)\| \\ &\leq M_2 \|x_0\| + \frac{M_2}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} \|z(s)\| ds + M_3 \|z(t)\| + K \\ &\leq (M_2 \|x_0\| + K) + \frac{M_2 R}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} ds + M_3 R \\ &= (M_2 \|x_0\| + K) + \left[\frac{M_2}{\Gamma(\alpha+1)} T^{\alpha} + M_3\right] R \\ &\leq R \left[ 1 - \left(\frac{M_2}{\Gamma(\alpha+1)} T^{\alpha} + M_3\right) \right] + \left[\frac{M_2 R}{\Gamma(\alpha+1)} T^{\alpha} + M_3 R\right] = R. \end{split}$$

This proves that any  $z \in C_L(J, B_R)$ ,  $Tz \in C(J, B_R)$ . Step 3: For any  $z \in C(J, B_R)$ , Tz is Lipschitz with Lipschitz constant L.

Let any  $z \in C_L(J, B_R)$  and  $t_1, t_2 \in J$  with  $t_1 < t_2$ . Then by Lipschitz type condition on f given in (A1) and the inequality (3.8), we obtain

$$\begin{split} \|(Tz)(t_1) - (Tz)(t_2)\| \\ &= \left\| f\left(t_1, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^{t_1} (t_1 - s)^{\alpha - 1} z(s) ds, z(t_1)\right) \right. \\ &- f\left(t_2, x_0 + \frac{1}{\Gamma(\alpha)} n t_0^{t_2} (t_2 - s)^{\alpha - 1} z(s) ds, z(t_2)\right) \right\| \\ &\leq M_1 |t_1 - t_2| + \frac{M_2}{\Gamma(\alpha)} \int_0^{t_1} \left[ (t_1 - s)^{\alpha - 1} - (t_2 - s)^{\alpha - 1} \right] \|z(s)\| ds \\ &+ \frac{M_2}{\Gamma(\alpha)} \int_{t_1}^{t_2} (t_2 - s)^{\alpha - 1} \|z(s)\| ds + M_3 \|z(t_2) - z(t_1)\| \\ &\leq M_1 |t_1 - t_2| + \frac{M_2 R}{\Gamma(\alpha)} \int_0^{t_1} \left[ (t_1 - s)^{\alpha - 1} - (t_2 - s)^{\alpha - 1} \right] ds \\ &+ \frac{M_2 R}{\Gamma(\alpha)} \int_{t_1}^{t_2} (t_2 - s)^{\alpha - 1} ds + M_3 L |t_2 - t_1| \end{split}$$

$$= (M_1 + M_3L) |t_1 - t_2| + \frac{M_2R}{\Gamma(\alpha + 1)} [(t_2 - t_1)^{\alpha} + t_1^{\alpha} - t_2^{\alpha}] + \frac{M_2R}{\Gamma(\alpha + 1)} (t_2 - t_1)^{\alpha}$$
  

$$\leq (M_1 + M_3L) |t_1 - t_2| + \frac{2M_2R}{\Gamma(\alpha + 1)} (t_2 - t_1)^{\alpha} = \left(M_1 + \frac{2M_2R}{\Gamma(\alpha + 1)} + M_3L\right) |t_2 - t_1|$$
  

$$\leq (L(1 - M_3) + M_3L) |t_2 - t_1| = L|t_2 - t_1|.$$

This shows that Tz is Lipschitz function with Lipschitz constant L. From Steps-1 to 3, we get  $Tz \in C_L(J, B_R)$ . Hence T is self mapping on  $C_L(J, B_R)$ .

Part-(II): To prove  $T : C_L(J, B_R) \to C_L(J, B_R)$  is a Picard Operator, we prove that T is contraction. Let any  $z_1, z_2 \in C_L(J, B_R)$ . Then for any  $t \in J$ , we have

$$\begin{split} \|T(z_{1})(t) - T(z_{2})(t)\| \\ &= \left\| f\left(t, x_{0} + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} z_{1}(s) ds, z_{1}(t)\right) \\ &- f\left(t, x_{0} + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} z_{2}(s) ds, z_{2}(t)\right) \right\| \\ &\leq \frac{M_{2}}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} \|z_{1}(s) - z_{2}(s)\| ds + M_{3} \|z_{1}(t) - z_{2}(t)\| \\ &\leq \frac{M_{2}}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} \mathbb{E}_{\alpha}(\theta s^{\alpha}) \sup_{s \in J} \left( \frac{\|(z_{1} - z_{2})(s)\|}{\mathbb{E}_{\alpha}(\theta s^{\alpha})} \right) ds + M_{3} \mathbb{E}_{\alpha}(\theta t^{\alpha}) \sup_{t \in J} \left( \frac{\|(z_{1} - z_{2})(t)\|}{\mathbb{E}_{\alpha}(\theta t^{\alpha})} \right) \\ &= \frac{M_{2} \|z_{1} - z_{2}\|_{B}}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} \mathbb{E}_{\alpha}(\theta s^{\alpha}) ds + M_{3} \mathbb{E}_{\alpha}(\theta t^{\alpha}) \|z_{1} - z_{2}\|_{B}. \end{split}$$

But,

$$I_{0,t}^{\alpha}E_{\alpha}(\theta t^{\alpha}) = \frac{1}{\theta}\left[E_{\alpha}(\theta t^{\alpha}) - 1\right] \le \frac{1}{\theta}E_{\alpha}(\theta t^{\alpha}), \ t \in J.$$

This gives

$$\|(Tz_1)(t) - (Tz_2)(t)\| \le \frac{M_2 \|z_1 - z_2\|_B}{\theta} \mathbb{E}_{\alpha}(\theta t^{\alpha}) + M_3 E_{\alpha}(\theta t^{\alpha}) \|z_1 - z_2\|_B, \ t \in J.$$

Therefore,

$$\begin{aligned} \|Tz_1 - Tz_2\|_B &= \sup_{t \in J} \left( \frac{\|(Tz_1 - Tz_2)(t)\|}{\mathbb{E}_{\alpha}(\theta t^{\alpha})} \right) \\ &\leq \left( \frac{M_2}{\theta} + M_3 \right) \|z_1 - z_2\|_B, \ t \in J. \end{aligned}$$

Since  $0 < M_3 < 1$ , we can choose sufficiently large  $\theta$ , so that  $\frac{M_2}{\theta} + M_3 < 1$ . This proves that  $T: C_L(J, B_R) \to C_L(J, B_R)$  is contraction and hence Picard operator. By contraction principle there is  $z^*$  in  $C_L(J, B_R)$  such that  $z^* = Tz^*$ . This  $z^*$  is the unique solution of functional integral equation (3.2). Further for any  $z \in C_L(J, B_R)$ ,  $||T^n z - z^*||_B \to 0$  as  $n \to \infty$ . Substituting this  $z^*$  in (3.1), we obtain the unique solution  $x^*$  of the nonlinear implicit FDEs (1.1)–(1.2).

#### **3.2** Dependency of solution Through Picard Operator Theory:

To investigate the data dependency of the solution of the nonlinear implicit FDEs (1.1)-(1.2), we consider the another nonlinear implicit FDEs of the form

$${}_{0}^{c}\mathcal{D}_{t}^{\alpha}x(t) = g\left(t, x(t), {}_{0}^{c}\mathcal{D}_{t}^{\alpha}x(t)\right), t \in [0, T],$$
(3.9)

$$x(0) = y_0 \in X, (3.10)$$

where  $g: J \times X \times X \to X$  is any nonlinear function need not equal to f.

**Theorem 3.3** Assume that the functions f and g satisfies the hypothesis (A1). Let there exists  $\eta \in L^1(J, \mathbb{R}_+) \cap C(J, \mathbb{R}_+)$  such that

$$||f(t, x, y) - g(t, x, y)|| \le \eta(t), \ t \in J, \ x, y \in X.$$

If the condition (3.4) holds and  $\theta > 0$  is such that  $\frac{M_2}{\theta} + M_3 < 1$ , then the solution  $x^*$  of (1.1)–(1.2) and the solution  $y^*$  of (3.9) –(3.10) satisfies the inequality

$$\|x^* - y^*\|_B \le \|x_0 - y_0\| + \frac{K_{\eta}}{\theta \left[1 - \left(\frac{M_2}{\theta} + M_3\right)\right]},\tag{3.11}$$

where  $K_{\eta} = \max \{\eta(t) : t \in J\}.$ 

*Proof:* By Lemma 3.1, the equivalent integral equation to the nonlinear implicit FDEs (3.9) - (3.10) is given by

$$x(t) = y_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, \ t \in J,$$
(3.12)

where z is the solution of the functional integral equation

$$z(t) = g\left(t, y_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), t \in J.$$
(3.13)

Since  $g: J \times X \times X \to X$  satisfies the conditions of Theorem 3.2, proceeding as in the proof of Theorem 3.2, the condition (3.4) allows us to choose  $\tilde{L} > 0$  and  $\tilde{R} > 0$  such that the mapping

$$S: C_{\tilde{L}}(J, B_{\tilde{R}}) \to C_{\tilde{L}}(J, B_{\tilde{R}})$$

defined by

$$S(z)(t) = g\left(t, y_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), \ t \in J$$

has unique fixed point  $F_S \in C_{\tilde{L}}(J, B_{\tilde{R}})$ . Define  $L^* = \max\{L, \tilde{L}\}$ . Then one can verify that  $F_T, F_S \in C_{L^*}(J, B_{R^*})$ .

Now, for any  $z \in C_{L^*}(J, B_{R^*})$  and  $t \in J$ , we have

$$||(Tz)(t) - (Sz)(t)||$$

$$= \left\| f\left(t, x_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right) - g\left(t, y_0 + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right) \right\|$$
  
$$\leq \eta(t) \leq K_\eta.$$

Since  $\mathbb{E}_{\alpha}(\theta t^{\alpha}) \geq 1$  for all  $t \in J$ , we have

$$||Tz - Sz||_B = \sup_{t \in J} \left( \frac{||(Tz - Sz)(t)||}{\mathbb{E}_{\alpha}(\theta t^{\alpha})} \right) \le K_{\eta}.$$

Since the operators T, S satisfies the conditions of Lemma 2.2, by applying it, we obtain

$$\|F_T - F_S\|_B \le \frac{K_\eta}{1 - \left(\frac{M_2}{\theta} + M_3\right)}.$$

Note that

$$x^{*}(t) = x_{0} + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} F_{T}(s) ds, \ t \in J;$$

and

$$y^{*}(t) = y_{0} + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} F_{S}(s) ds, \ t \in J;$$

are the unique solutions of nonlinear implicit FDEs (1.1)–(1.2) and (3.9) –(3.10) respectively. Then for any  $t \in J$ , we have

$$\begin{aligned} \|x^{*}(t) - y^{*}(t)\| &\leq \|x_{0} - y_{0}\| + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t - s)^{\alpha - 1} \|F_{T}(s) - F_{S}(s)\| ds \\ &\leq \|x_{0} - y_{0}\| + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t - s)^{\alpha - 1} \mathbb{E}_{\alpha} \left(\theta s^{\alpha}\right) \sup_{s \in J} \left(\frac{\|F_{T}(s) - F_{S}(s)\|}{\mathbb{E}_{\alpha} \left(\theta s^{\alpha}\right)}\right) ds \\ &= \|x_{0} - y_{0}\| + \frac{\|F_{T} - F_{S}\|_{B}}{\Gamma(\alpha)} \int_{0}^{t} (t - s)^{\alpha - 1} \mathbb{E}_{\alpha} \left(\theta s^{\alpha}\right) ds \\ &= \|x_{0} - y_{0}\| + \|F_{T} - F_{S}\|_{B} \left(\frac{\mathbb{E}_{\alpha} \left(\theta t^{\alpha}\right) - 1}{\theta}\right) \\ &\leq \|x_{0} - y_{0}\| + \frac{\mathbb{E}_{\alpha} \left(\theta t^{\alpha}\right) K_{\eta}}{\theta \left[1 - \left(\frac{M_{2}}{\theta} + M_{3}\right)\right]}. \end{aligned}$$

This gives,

$$\|x^* - y^*\|_B = \sup_{t \in J} \left( \frac{\|(x^* - y^*)(t)\|}{\mathbb{E}_{\alpha} \left(\theta t^{\alpha}\right)} \right) \le \|x_0 - y_0\| + \frac{K_{\eta}}{\theta \left[ 1 - \left(\frac{M_2}{\theta} + M_3\right) \right]},$$

which is the desired inequality (3.11).

#### Remark:

- (1) Theorem 3.3 gives the dependence of the solution of the problem (1.1)-(1.2) on the initial condition as well as on the functions involved on the right-hand side.
- (2) If  $K_{\eta} = 0$  in (3.11), that is when f = g, Theorem 3.3 gives the dependency of solution of (1.1)-(1.2) on initial condition.
- (3) If  $x_0 = y_0$  and  $K_\eta \neq 0$  in (3.11), then Theorem 3.3 gives the dependency of solution of (1.1)-(1.2) on functions involved in the right hand side of equation.
- (4) If  $x_0 = y_0$  and  $K_{\eta} = 0$  in (3.11), Theorem 3.3 gives the uniqueness of solution of the problem (1.1)-(1.2).

#### 3.3 Dependency of solution through Pompeiu–Hausdorff functional

Next, we consider an equation of the form,

$$x_z(t) = z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, \ t \in J;$$
(3.14)

where z is a solution of fractional functional equation

$$z(t) = f\left(t, z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), t \in J,$$
(3.15)

where f is as in the problem (1.1)-(1.2). From equations (3.14)–(3.15) it follows that  $x_z(0) = z(0) = f(0, z(0), z(0))$ 

**Theorem 3.4** Let  $f: J \times X \times X \to X$  satisfies the assumptions (A1) and f(0, x, x) = x, for all  $x \in X$ . Then the equation (3.14) has a solution in  $C_L(J, B_R)$  for some L, R > 0. If  $\mathcal{S} \subset C_L(J, B_R)$  is its solution set, then card  $\mathcal{S} = \text{card } B_R$ .

*Proof:* Consider the operator  $T_*: (C_L(J, B_R), \|\cdot\|_B) \to (C_L(J, B_R), \|\cdot\|_B)$  defined by,

$$T_*(z)(t) = f\left(t, z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), \ t \in J$$
(3.16)

Proceeding as in proof of Theorem 3.2, there exist constants L, R > 0 such that  $T_*$  is a continuous operator on  $C_L(J, B_R)$ . One can verify that, the operator  $T_*$  does not satisfies Lipschitz condition and hence  $T_*$  is not a Picard operator.

Next, We apply Lemma 2.1 to prove that the operator  $T_*$  is a weakly Picard operator. For each  $\alpha \in B_R$ , we define  $X_{\alpha} = \{z \in C_L(J, B_R) : z(0) = \alpha\}$ . Clearly,  $C_L(J, B_R) = \bigcup_{\alpha \in B_R} X_{\alpha}$ . By assumption for any  $z \in X_{\alpha}$ , we have

$$T_*(z)(0) = f(0, z(0), z(0)) = f(0, \alpha, \alpha) = \alpha.$$

Therefore, for each  $\alpha \in B_R$ ,  $X_{\alpha}$  is invariant under  $T_*$ . Proceeding as in the proof of Theorem (3.2), one can verify that for each  $\alpha \in B_R$ , the operator  $T_*|_{X_{\alpha}} : X_{\alpha} \to X_{\alpha}$  is a

Picard operator. Using Lemma 2.1,  $T_*$  is weakly Picard operator. By definition 2.2, for any  $x_0 \in C_L(J, B_R)$  the seq  $T_*^n(x_0)$  converges to the fixed point of  $T^*$ , which is the solution of fractional functional equation (3.15), from which we can obtain the solution of (3.14). Following the similar steps of Theorem 4.1 of [35], one can complete the proof of

card 
$$\mathcal{S} = \text{card } B_R$$
.

In order to discuss the data dependency of solution, we consider the equations (3.14)–(3.15), and the equations

$$x_z(t) = z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, \ t \in J,$$
(3.17)

where z is a solution of functional equation

$$z(t) = g\left(t, \tilde{z}(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right), t \in J,$$
(3.18)

and  $g \in C(J \times X \times X, X)$  is any other nonlinear function need not equal to f.

**Theorem 3.5** Assume that f and g satisfies the hypothesis (A1) and f(0, x, x) = x = g(0, x, x) for all  $x \in X$ . Let there exists K > 0 such that

$$||f(t,x,y) - g(t,x,y)|| \le K \mathbb{E}_{\alpha}(\theta t^{\alpha}), \ t \in J, \ x,y \in X,$$

for sufficiently large  $\theta > 0$  satisfying  $\frac{M_2}{\theta} + M_3 < 1$ . If S and  $\hat{S}$  are the solution sets of the equation (3.15) and (3.17) respectively, then there exists  $L^*$ ,  $R^* > 0$  such that

$$H_{\|\cdot\|_{B}}\left(\mathcal{S},\hat{\mathcal{S}}\right) \leq \frac{KT^{\alpha}}{\Gamma(\alpha+1)\left[1-\left(\frac{M_{2}}{\theta}+M_{3}\right)\right]},\tag{3.19}$$

where  $H_{\|\cdot\|_B}$  is the Pompeiu-Hausdorff functional with respect to  $\|\cdot\|_B$  on  $C_{L^*}(J, B_{R^*})$ .

*Proof:* Since  $g: J \times X \times X \to X$  satisfies the conditions of Theorem 3.4, proceeding as in the proof of Theorem 3.4, we can choose  $\tilde{L} > 0$  and  $\tilde{R} > 0$  such that the mapping

$$S_*: \left(C_{\tilde{L}}(J, B_{\tilde{R}}), \|\cdot\|_B\right) \to \left(C_{\tilde{L}}(J, B_{\tilde{R}}), \|\cdot\|_B\right)$$

defined by

$$S_*(z)(t) = g\left(t, z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right)$$
(3.20)

has a fixed point  $F_{S_*} \in C_{\tilde{L}}(J, B_{\tilde{R}})$ . Define  $L^* = \max\{L, \tilde{L}\}$  and  $R^* = \max\{R, \tilde{R}\}$ , then one can verify that  $F_{T_*}, F_{S_*} \in C_{L^*}(J, B_{R^*})$ . Now, for any  $z \in C_{L^*}(J, B_{R^*})$  and  $t \in J$ , we have

$$\begin{split} \|T_{*}^{2}(z)(t) - T_{*}(z)(t)\| &= \|T_{*}(T_{*}(z)(t)) - T_{*}z(t)\| \\ &= \left\| f\left(t, T_{*}(z)(0) + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} T_{*}(z(s)) ds, T_{*}(z(t))\right) \right) \\ &- f\left(t, z(0) + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} z(s) ds, z(t)\right) \right\| \\ &\leq M_{2} \left\| \left( z(0) + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} T_{*}(z(s)) ds \right) - \left( z(0) + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} z(s) ds \right) \right\| \\ &+ M_{3} \|T_{*}(z)(t) - z(t)\| \\ &\leq \frac{M_{2}}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} \|T_{*}(z(s)) - z(s)\| ds + M_{3} \|T_{*}(z)(t) - z(t)\| \\ &\leq \frac{M_{2}}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} \mathbb{E}_{\alpha}(\theta s^{\alpha}) \frac{\|T_{*}(z(s)) - z(s)\|}{\mathbb{E}_{\alpha}(\theta s^{\alpha})} ds + M_{3} \mathbb{E}_{\alpha}(\theta t^{\alpha}) \frac{\|T_{*}(z(t)) - z(t)\|}{\mathbb{E}_{\alpha}(\theta t^{\alpha})} \\ &\leq \frac{M_{2}}{\Gamma(\alpha)} \|T_{*}(z) - z\|_{B} \int_{0}^{t} (t-s)^{\alpha-1} \mathbb{E}_{\alpha}(\theta s^{\alpha}) ds + M_{3} \mathbb{E}_{\alpha}(\theta t^{\alpha}) \|T(z) - z\|_{B} \\ &\leq M_{2} \|T_{*}(z) - z\|_{B} \frac{\mathbb{E}_{\alpha}(\theta t^{\alpha})}{\theta} + M_{3} \mathbb{E}_{\alpha}(\theta t^{\alpha}) \|T_{*}(z) - z\|_{B}. \end{split}$$

This gives

$$\frac{\|T_*^2 z(t) - T_* z(t)\|}{\mathbb{E}_{\alpha}(\theta t^{\alpha})} \le \frac{M_2}{\theta} \|T_* z - z\|_B + M_3 \|T_* z - z\|_B$$

Therefore

$$\|T_*^2 z - T_* z\|_B \le \frac{M_2}{\theta} \|T_* z - z\|_B + M_3 \|T_* z - z\|_B = \left(\frac{M_2}{\theta} + M_3\right) \|T_* z - z\|_B, \ z \in C_{L^*}(J, B_{R^*}).$$

On the similar line, we have

$$\|S_*^2 z - S_* z\|_B \le \left(\frac{M_2}{\theta} + M_3\right) \|S_* z - z\|_B, \ z \in C_{L^*}(J, B_{R^*})$$

Further, for any  $z \in C_{L^*}(J, B_{R^*})$  and  $t \in J$ , we have

$$\begin{aligned} \|T_*(z)(t) - S_*(z)(t)\| \\ &= \left\| f\left(t, z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right) \right. \\ &\left. -g\left(t, z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} z(s) ds, z(t)\right) \right\| \\ &\leq K \mathbb{E}_\alpha(\theta t^\alpha) \end{aligned}$$

This gives,

$$\|T_*z - S_*z\|_B = \sup_{t \in J} \frac{\|T_*z(t) - S_*z(t)\|}{\mathbb{E}_{\alpha}(\theta t^{\alpha})} \le K, \ z \in C_{L^*}(J, B_{R^*}).$$

Since, the operators  $T_*$ ,  $S_*$  fulfills the requirements of Lemma (2.3), by an application of it, we obtain

$$H_{\|\cdot\|_B}(F_{T_*}, F_{S_*}) \le \frac{K}{1 - \left(\frac{M_2}{\theta} + M_3\right)}.$$

Note that

$$x_{z}^{*}(t) = z(0) + \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} F_{T_{*}}(s) ds, \ t \in J;$$

and

$$y_z^*(t) = z(0) + \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} F_{S_*}(s) ds, \ t \in J;$$

are the solutions of (3.14) and (3.17) respectively. Therefore, for any  $t \in J$ , we have

$$\|x_z^*(t) - y_z^*(t)\| \le \frac{1}{\Gamma(\alpha)} \int_0^t (t-s)^{\alpha-1} \|F_{T_*}(s) - F_{S_*}(s)\| ds$$

This gives,

$$H_{\|\cdot\|_{B}}(x_{z}^{*}, y_{z}^{*}) \leq \frac{1}{\Gamma(\alpha)} \int_{0}^{t} (t-s)^{\alpha-1} H_{\|\cdot\|_{B}}(F_{T_{*}}, F_{S_{*}}) ds$$

$$\leq \frac{K}{\Gamma(\alpha) \left[1 - \left(\frac{M_{2}}{\theta} + M_{3}\right)\right]} \int_{0}^{t} (t-s)^{\alpha-1} ds$$

$$= \frac{Kt^{\alpha}}{\Gamma(\alpha+1) \left[1 - \left(\frac{M_{2}}{\theta} + M_{3}\right)\right]}$$

$$\leq \frac{KT^{\alpha}}{\Gamma(\alpha+1) \left[1 - \left(\frac{M_{2}}{\theta} + M_{3}\right)\right]}$$

Therefore,

$$H_{\|\cdot\|_B}\left(\mathcal{S},\hat{\mathcal{S}}\right) \leq \frac{KT^{\alpha}}{\Gamma(\alpha+1)\left[1-\left(\frac{M_2}{\theta}+M_3\right)\right]},$$

which is the desired inequality (3.19)

**Remark 3.6** Theorem 3.5, gives the dependency of solution on functions involved in the right hand side of the problem (3.14)-(3.15). In particular, if K = 0 then f = g, and we obtain uniqueess of the solution.

# 4 Example

Consider the nonlinear implicit FDEs of the form,

$${}_{0}^{c}\mathcal{D}_{t}^{\frac{1}{2}}x(t) = \frac{\sqrt{\pi}}{4} - \frac{1}{2}t^{\frac{1}{2}} + \frac{1}{2}\left(x(t) + |{}_{0}^{c}\mathcal{D}_{t}^{\frac{1}{2}}x(t)|\right), t \in J := [0, 0.5], \tag{4.1}$$

$$x(0) = 1 \in X \tag{4.2}$$

in the Banach space  $X=(\mathbb{R},|\cdot|).$  Define  $f:J\times X\times X\to X$  by

$$f(t, x, y) = \frac{\sqrt{\pi}}{4} - \frac{1}{2}t^{\frac{1}{2}} + \frac{1}{2}\left(x + |y|\right)$$

For any  $t_1, t_2 \in J$  and  $x_i, y_i \in X$ , i = 1, 2, we have

$$\begin{aligned} |f(t_1, x_1, y_1) - f(t_2, x_2, y_2)| &= \left| \left( \frac{\sqrt{\pi}}{4} - \frac{1}{2} t_1^{\frac{1}{2}} + \frac{1}{2} \left( x_1 + |y_1| \right) \right) - \left( \frac{\sqrt{\pi}}{4} - \frac{1}{2} t_2^{\frac{1}{2}} + \frac{1}{2} \left( x_2 + |y_2| \right) \right) \right| \\ &\leq \frac{1}{2} |t_1^{\frac{1}{2}} - t_2^{\frac{1}{2}}| + \frac{1}{2} \left( |x_1 - x_2| + ||y_1| - |y_2|| \right) \\ &\leq \frac{1}{2} |t_1 - t_2| + \frac{1}{2} \left( |x_1 - x_2| + |y_1 - y_2| \right) \end{aligned}$$

Therefore, the function f satisfies hypothesis (A1) with constants  $M_1 = M_2 = M_3 = \frac{1}{2}$ . Note that,

$$\frac{M_2 T^{\alpha}}{\Gamma(\alpha+1)} + M_3 = \frac{\frac{1}{2}(0.5)^{\frac{1}{2}}}{\Gamma(\frac{3}{2})} + M_3 = \sqrt{\frac{0.5}{\pi}} + \frac{1}{2} = 0.8989 < 1.$$

Since the function f satisfies all conditions of Theorem 3.2, the problem (4.1)–(4.2) has unique solution. By direct calculation one can verify that the solution of the problem (4.1)–(4.2) is

$$x^*(t) = t^{\frac{1}{2}} + \mathbb{E}_{\frac{1}{2}}(t^{\frac{1}{2}}), t \in J.$$

Next, we consider another implicit FDEs

$${}_{0}^{c}\mathcal{D}_{t}^{\frac{1}{2}}x(t) = \frac{t^{\frac{1}{2}}}{2} + \frac{1}{2}\left(x(t) + |{}_{0}^{c}\mathcal{D}_{t}^{\frac{1}{2}}x(t)|\right), t \in [0, 0.5],$$

$$(4.3)$$

$$x(0) = 1 - \frac{\sqrt{\pi}}{2} \in X \tag{4.4}$$

Define  $g: J \times X \times X \to X$  by

$$g(t, x, y) = \frac{t^{\frac{1}{2}}}{2} + \frac{1}{2} \left( x(t) + |_0^c \mathcal{D}_t^{\frac{1}{2}} x(t)| \right), \ t \in J.$$

One can verify that the function  $g: J \times X \times X \to X$  defined by

$$g(t, x, y) = \frac{t^{\frac{1}{2}}}{2} + \frac{1}{2} \left( x + |y| \right),$$

satisfies all conditions of Theorem 3.2 with constants  $M_1 = M_2 = M_3 = \frac{1}{2}$ . One can verify that

$$y^*(t) = t^{\frac{1}{2}} + \mathbb{E}_{\frac{1}{2}}(t^{\frac{1}{2}}) - \frac{\sqrt{\pi}}{2}, \ t \in J.$$

is a exact solution of (4.3)-(4.4). Note that for any  $t \in J$  and  $x, y \in X$ 

$$\begin{aligned} |f(t,x,y) - g(t,x,y)| &= \left| \left( \frac{\sqrt{\pi}}{4} - \frac{1}{2} t^{\frac{1}{2}} + \frac{1}{2} \left( x + |y| \right) \right) - \left( \frac{t^{\frac{1}{2}}}{2} + \frac{1}{2} \left( x + |y| \right) \right) \right| \\ &= \left| \frac{\sqrt{\pi}}{4} - t^{\frac{1}{2}} \right| \le \frac{\sqrt{\pi}}{4} + t^{\frac{1}{2}} := \eta(t). \end{aligned}$$

Since f, g satisfies all the conditions of Theorem 3.3, by applying it, we obtain

$$\|x^* - y^*\|_B \le \|x_0 - y_0\| + \frac{K_{\eta}}{\theta \left[1 - \left(\frac{M_2}{\theta} + M_3\right)\right]},\tag{4.5}$$

where  $K_{\eta} = \max_{t \in J} \eta(t) = \max_{t \in J} \left( \frac{\sqrt{\pi}}{4} + t^{\frac{1}{2}} \right) = \frac{\sqrt{\pi}}{4} + (0.5)^{\frac{1}{2}} = 1.1502$ . Take  $\theta = 2$ , we have  $\frac{M_2}{\theta} + M_3 < 1$ . With this choice of  $\theta$ , from (4.5), we have

$$\|x^* - y^*\|_B \le |1 - (1 - \frac{\sqrt{\pi}}{2})| + \frac{1.1502}{2[1 - 0.75]} = \frac{\sqrt{\pi}}{2} + 2.3004$$
(4.6)

Using the exact solution and by actual calculation, we have

$$\|x^* - y^*\|_B = \sup_{t \in J} \frac{|x^* - y^*|}{\mathbb{E}_{\frac{1}{2}}(\theta t^{\frac{1}{2}})} \le |x^* - y^*| = \frac{\sqrt{\pi}}{2} < \frac{\sqrt{\pi}}{2} + 2.3004$$
(4.7)

**Remark 4.1** Form the inequalities (4.6) and (4.7), it is observed that the difference of solution calculated by applying Theorem 3.3 is similar to the difference of solution that calculated actually.

## 5 Concluding remarks

Observing the applicability of Caputo–Fabrizio (CF) fractional derivative operator [39]-[41] and Atangana–Baleanu–Caputo (ABC) fractional derivative operator [43, 44, ?] that possesses a non-singular kernel, one can analyze and extend results of the present papers for the implicit FDEs with CF and ABC fractional derivative operators.

## References

- K. Diethelm, A. D. Freed, On the solution of nonlinear fractional order differential equations used in the modeling of viscoplasticity, in: F. Keil, W. Mackens, H. Voss, J. Werther (Eds), Scientific Computing in Chemical Engineering II- Computational Fluid Dynamics, Reaction Engineering and Molecular Properties, Springer- Verlag, Heidelberg, 1999, 217-224.
- [2] W. G. Glockle, T. F. Nonnenmacher, A fractional calculus approach of self-similar protein dynamics, *Biophys. J.*, 68 (1995), 45-63.
- [3] R. Hilfer, Application of Fractional Calculus in Physics, World Scientific, Singapore, 2000.
- [4] F. Mainardi, Fractional Calculus: Some basis problems in continuum and statistical mechanics, in: A. Carpinteri, F. Mainardi (Eds), Fractals and Fractional calculus in Continuum Mechanics, Springer- Verlag, Wein, 1997, 291-348.
- [5] F. Metzler, W. Schick, H. G. Killian, T. F. Nonnenmacher, Relaxation in filled polymers: A fractional calculus approach, J. Chem. Phys., 103 (1995).
- [6] V. E. Tarasov, Fractional Dynamics: Application of Fractional Calculus to Dynamics of Particles, *Field and Media, Springer*, HEP, 2011.
- [7] A. A. Kilbas, H. M. Srivastava, J. J. Trujillo, Theory and Application of Fractional Differential Equations, *Elsevier Science B. V.*, 2006.
- [8] V. Lakshmikamntham, S. Leela, J. V. Devi, Theory of Fractional Dynamic Systems, *Cambridge, Scientific Publisher*, 2009.
- [9] I. Podlubny, Fractional Differential Equations, Academic Press, 1999.
- [10] K. Diethelm, The Analysis of Fractional Differential Equations, Lecture Notes in Mathematics, Springer, 2010.
- [11] V. Lakshmikantham, A. S. Vatsala, Theory of Fractional Functional Differential Equations, Nonlinear Analysis, 69 (2008), 3337-3343.
- [12] V. Lakshmikantham, A. S. Vatsala, General uniqueness and monotone iterative technique for fractional differential equations, *Applied Mathematics Letters*, 21 (2008), 828-834.
- [13] V. Lakshimikantham, S. Leela, Basic Theory of fractional differential equations, Nonlinear Analysis, 69 (2008), 2677-2682.
- [14] V Daftardar-Gejji, A Babakhani, Analysis of a system of fractional differential equations, Journal of Mathematical Analysis and Applications, 293 (2), 511-522.
- [15] K. Diethelm, N.J. Ford, Analysis of fractional differential equations, J. Math. Anal. Appl., 265 (2002), 229-248.

- [16] R. P. Agarwal, Yong Zhou, Yunyun Heb, Existence of fractional neutral functional differential equations, Computers and Mathematics with Applications, 59 (2010), 1095-1100.
- [17] J. Wang, L. Lv, Y. Zhou, Ulam stability and data dependence for fractional differential equations with Caputo derivative, *Electronic Journal of Qualitative Theory of Differential Equations*, 63 (2011), 1–10.
- [18] C. Ravichandran, N. Valliammal and Juan J Nieto, New results on exact controllability of a class of fractional neutral integro-differential systems with state-dependent delay in Banach spaces, *Journal of the Franklin Institute*, 356(3) (2019), 1535–1565.
- [19] K. Jothimani, K Kaliraj, Zakia Hammouch and C. Ravichandran, New results on controllability in the framework of fractional integrodifferential equations with nondense domain, *The European Physical Journal Plus*, 134 (441), (2019).
- [20] N. D. Cong, H. T. Tuan, H. Trinh, On asymptotic properties of solutions to fractional differential equations, *Journal of Mathematical Analysis and Applications*, 484(2) (2020).
- [21] G. Iskenderoglu, D. Kaya, Symmetry analysis of initial and boundary value problems for fractional differential equations in Caputo sense, *Chaos, Solitons and Fractals* 134 (2020), 109684.
- [22] D. Li, Peano's theorem for implicit differential equations, J. Math. Anal. Appl. 258 (2001), 591-616.
- [23] M. Benchohra, J. Lazreg, Nonlinear fractional implicit fractional differential equations, Commun. Appl. Anal., 17 (2013), 471-482.
- [24] M. Benchohra, J. Lazreg, Existence and uniqueness results for nonlinear implicit fractional differential equations with boundary conditions, *Rom. J. Math. Comput. Sci.*, 4 (2014), 60-72.
- [25] J. J. Nieto, A. Ouahab, V. Venktesh, Implicit Fractional Differential Equations via the LiouvilleCaputo Derivative, *Mathematics*, 3 (2015), 398-411.
- [26] M. Benchohra, M. Said Souid, Integrable solutions for implicit fractional order differential equations, *Nonlinear Analysis*, 69 (2008), 2677-2682.
- [27] M. Benchohra, M. Said Souid,  $L^1$ -Solutions for Implicit Fractional Order Differential Equations with Nonlocal Conditions, *Filomat* 30 :6 (2016), 1485–1492.
- [28] M. Benchohra, M. Said Souid, L<sup>1</sup>-Solutions of boundary value problem for implicit fractional order differential equations, Surveys in Mathematics and its Applications, 10 (2015), 4959.
- [29] D. Vivek, K. Kanagarajan, E. M. Elsayed, Some Existence and Stability Results for Hilfer-fractional Implicit Differential Equations with Nonlocal Conditions, *Mediter*ranean Journal of Mathematics, 15 (2018), 273-293.

- [30] K. D. Kucche, J. J. Nieto, V. Venktesh, Theory of nonlinear implicit fractional differential equations, *Differ. Equ. Dyn. Syst.* 28 (2020),1–17.
- [31] K. D. Kucche, S. T. Sutar, Stability via successive approximations for nonlinear implicit fractional differential equations, *MJPAA* DOI 10.1515/3(1),2017,36-55.
- [32] S. T. Sutar, K. D. Kucche, Global existence and uniqueness for implicit differential equations of arbitrary order, *Fractional Differential Calculus* 5(2)(2015), 199-208.
- [33] I. A. Rus, Functional Differential equations of fixed type via weakly picards operators. Seminar on Fixed Point Theory Cluj-Napoca, 3 (2002), 335-345.
- [34] I. A. Rus, Weakly Picard Operators and Applications, Seminar on Fixed Point Theory Cluj-Napoca, 2 (2001), 41-58.
- [35] J. Wang, Y. Zhou, M. Medved, Picard and weakly Picard operator technique for nonlinear differential equations in Banach spaces, J. Math. Anal. Appl., 389 (2012), 261-274.
- [36] D. Otrocol, V. Ilea, Qualitative properties of functional differential equation, Electronic Journal of Qualitative Theory of Differential Equations, 2014. 1-8, 10.14232/ejqtde.2014.1.47.
- [37] D. Otrocol, V. Ilea, On the qualitative properties of functional integral equations with abstract Volterra operators, *Results in Fixed Point Theory and Applications*, 2018, Article ID 201813, 08 pages.
- [38] I. A. Rus, Metrical Fixed point theorems, Univ. of Cluj-Napoca, 1979.
- [39] M. Caputo, M. Fabrizio, A new definition of fractional derivative without singular kernel, Prog. Fract. Differ. Appl., 1(2)(2015), 73–85.
- [40] M. S. Aydogan, D. Baleanu, A. Mousalou, S. Rezapour, On approximate solutions for two higher-order Caputo-Fabrizio fractional integro-differential equations, Advances in Difference Equations, 221 (2017), https://doi.org/10.1186/s13662-017-1258-3.
- [41] D. Baleanu, A. Jajarmi, H. Mohammadi, S. Rezapour, A new study on the mathematical modelling of human liver with Caputo-Fabrizio fractional derivative, *Chaos, Solitons and Fractals*, 134 (2020), 109705, https://doi.org/10.1016/j.chaos.2020.109705.
- [42] A. Jajarmi, B.Ghanbari, D. Baleanu, A new and efficient numerical method for the fractional modeling and optimal control of diabetes and tuberculosis co-existence, *Chaos: An Interdisciplinary Journal of Nonlinear Science*, (9) 29 (2019),093111, https://doi.org/10.1063/1.5112177.
- [43] A. Atangana, D. Baleanu, New fractional derivatives with nonlocal and non-singular kernel Theory and application to heat transfer model, Therm. Sci., (2) 20 (2016), 763– 769.
- [44] D. Baleanu, A. Jajarmi, S.S.Sajjadi, D. Mozyrska, A new fractional model and optimal control of a tumor-immune surveillance with non-singular derivative operator, *Chaos: An Interdisciplinary Journal of Nonlinear Science*, (8) 29 2019, :083127, https://doi.org/10.1063/1.5096159.