

STUDY OF ENRICHED RATIONAL CONTRACTIONS IN CONVEX METRIC SPACE

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Abstract: This paper introduces and investigates two classes of enriched contraction mappings, namely enriched Jaggi contractions and enriched Dass and Gupta contractions, in the framework of convex metric spaces. For a continuous self-mapping on a complete convex metric space, fixed point theorems are established for both classes, proving the existence and uniqueness of a fixed point. In addition, a Krasnoselskij iterative method is employed to approximate the fixed point, and the corresponding iterative sequence is shown to converge to the unique fixed point for every initial point. Furthermore, the introduced enriched Jaggi and enriched Dass and Gupta contractions are extended to convex G -metric space, where analogous existence, uniqueness, and convergence results are established. The relationship of the obtained results with several well-known contraction mappings, including Banach, Jaggi and Dass and Gupta contractions, is demonstrated through suitable corollaries. Finally, an example is presented to illustrate the applicability of the proposed enriched contractions and the convergence of the associated iterative process.

Keywords and Phrases: Enriched Contraction, Convex Metric, G -metric space, Complete metric space, Krasnoselskij iteration.

2020 Mathematics Subject Classification: 47H10, 54H25.

1. Introduction

For over a hundred years, the fixed point hypothesis has been an important area of research in mathematics and various other sciences. This hypothesis serves as the cornerstone of functional analysis, which is essential in mathematics. The works of Liouville [14] and Picard [16], published in 1837 and 1890, respectively, are known to include the initial concepts of fixed-point theory. Banach [2] made a significant contribution by introducing the fundamental fixed-point theorem. Since then, many researchers have worked to expand and generalize the Banach fixed point theorem, leading to an array of new findings in recent years. Notable, we focus on two important fixed point theorems developed by Jaggi [11] and Dass and Gupta [8].

In 1970, Takahashi [22] introduced the concept of a convex structure in a metric space, which is now referred to as a convex metric space.

Definition 1.1. [22] *Let (H, d) be a metric space. A continuous mapping $W : H \times H \times [0, 1] \rightarrow H$ is said to be convex structure if there exists $u_1, u_2 \in H$ and $\mu \in [0, 1)$ such that*

$$d(u_3, W(u_1, u_2, \mu)) \leq \mu d(u_3, u_1) + (1 - \mu)d(u_3, u_2) \quad (1.1)$$

for any $u_3 \in H$.

A metric space (H, d) with a convex structure W is represented by (H, d, W) and is known as convex metric space.

This notion of convexity has proven to be an important tool for demonstrating various fixed point results (see [3], [7], [9], [10], [15]).

In recent years, the concept of an enriched contraction mappings has been used in convex metric space and Banach space to develop a more general version of classical fixed-point theorems. These enriched versions help us better understand the behavior of mappings in complicated spaces and improve the study of fixed points. In 2020, Brinde and Păcurar [4] introduced the concept of enriched contraction and proved some fixed-point results for such contraction mappings. Then in 2021, Brinde and Păcurar [5] also introduced the enriched Chatterjea contraction, which is a broader form of the original Chatterjea contraction. In 2022, Panicker and Shukla [17] obtained stability results of fixed points associated with the enriched contraction mappings in the framework of convex metric space. Later, Rawat and others [18] defined and studied new types of enriched contractions inspired by Kannan, Hardy-Rogers and Matkowski again in convex metric space. Anjali et al. [1] introduced enriched versions of Ćirić-type and Hardy-Rogers contractions, for which they established fixed point results. Recently, in 2024, Rani et al. [19] proposed the theory of enriched contraction mapping by introducing a new type

of contraction mappings known as hybrid enriched contractions in convex metric spaces.

The primary goal of the current work is to generalize some of the contraction mappings for enriched contractions within a convex metric space. An enriched Jaggi contraction and enriched Dass and Gupta contraction maps in convex metric space are defined in Section 2 of this study and are used to demonstrate the presence and uniqueness of fixed point using Kransnoselskij iterative technique ([13], [21]). In Section 3, the concept of an enriched Jaggi contraction and enriched Dass and Gupta contraction maps are extended in the convex G -metric space.

2. Main Results

In the present section, we introduce the concept of enriched Jaggi contraction and enriched Dass and Gupta contraction in the framework of a convex metric space.

Definition 2.1. Let (H, d, W) be a convex metric space. A mapping $R : H \rightarrow H$ is called an enriched Jaggi contraction if there exist $r_1, r_2 \geq 0$ and $\mu \in [0, 1)$ such that

$$d(W(u_1, Ru_1, \mu), W(u_2, Ru_2, \mu)) \leq r_1 d(u_1, u_2) + r_2 \frac{d(u_1, W(u_1, Ru_1, \mu)) \cdot d(u_2, W(u_2, Ru_2, \mu))}{d(u_1, u_2)} \quad (2.1)$$

for all distinct $u_1, u_2 \in H$ and $r_1 + r_2 < 1$.

Definition 2.2. Let (H, d, W) be a convex metric space. A mapping $R : H \rightarrow H$ is called an enriched Dass and Gupta contraction if there exist $r_1, r_2 \geq 0$ and $\mu \in [0, 1)$ such that

$$d(W(u_1, Ru_1, \mu), W(u_2, Ru_2, \mu)) \leq r_1 d(u_1, u_2) + r_2 \frac{d(u_2, W(u_2, Ru_2, \mu)) \cdot (1 + d(u_1, W(u_1, Ru_1, \mu)))}{(1 + d(u_1, u_2))} \quad (2.2)$$

for all distinct $u_1, u_2 \in H$ and $r_1 + r_2 < 1$.

Theorem 2.1. Let (H, d, W) be a complete convex metric space and $R : H \rightarrow H$ be a continuous mapping. Assume that R is an enriched Jaggi contraction map. Then

- (i) $Fix(R) = u$, for some $u \in H$.
- (ii) The sequence $u_{n+1} = W(u_n, Ru_n, \mu)$, $n \geq 0$, converges to u , for any $u_0 \in H$.
- (iii) The following inequality holds

$$d(u_{n+m}, u) \leq \frac{\nu^n}{1 - \nu} d(u_n, u_{n-1}), n, m \geq 1, \quad (2.3)$$

where $\nu = \frac{r_1}{1-r_2}$.

Proof. Define $R_\mu \mathbf{u} = W(\mathbf{u}, R\mathbf{u}, \mu)$, then $\text{Fix}(R) = \text{Fix}(R_\mu)$ (by Lemma 4 in [6]). By (2.1), we have $R_\mu : H \rightarrow H$ such that

$$d(R_\mu \mathbf{u}_1, R_\mu \mathbf{u}_2) \leq r_1 d(\mathbf{u}_1, \mathbf{u}_2) + r_2 \frac{d(\mathbf{u}_1, R_\mu \mathbf{u}_1) \cdot d(\mathbf{u}_2, R_\mu \mathbf{u}_2)}{d(\mathbf{u}_1, \mathbf{u}_2)}, \quad (2.4)$$

which implies that R_μ is enriched Jaggi contraction. Define $R_\mu \mathbf{u}_n = \mathbf{u}_{n+1}$, such that $\mathbf{u}_n \neq \mathbf{u}_{n+1}$, $\forall n \geq 0$.

Let $\mathbf{u}_1 = \mathbf{u}_{n-1}$ and $\mathbf{u}_2 = \mathbf{u}_n$ in (2.1) to get

$$\begin{aligned} d(\mathbf{u}_n, \mathbf{u}_{n+1}) &\leq r_1 d(\mathbf{u}_{n-1}, \mathbf{u}_n) + r_2 \frac{d(\mathbf{u}_{n-1}, \mathbf{u}_n) \cdot d(\mathbf{u}_n, \mathbf{u}_{n+1})}{d(\mathbf{u}_{n-1}, \mathbf{u}_n)} \\ d(\mathbf{u}_n, \mathbf{u}_{n+1}) &= r_1 d(\mathbf{u}_{n-1}, \mathbf{u}_n) + r_2 d(\mathbf{u}_n, \mathbf{u}_{n+1}) \\ d(\mathbf{u}_n, \mathbf{u}_{n+1}) &\leq \frac{r_1}{1-r_2} d(\mathbf{u}_{n-1}, \mathbf{u}_n) \\ d(\mathbf{u}_n, \mathbf{u}_{n+1}) &\leq \nu d(\mathbf{u}_{n-1}, \mathbf{u}_n) \\ d(\mathbf{u}_n, \mathbf{u}_{n+1}) &\leq \nu^n d(\mathbf{u}_0, \mathbf{u}_1) \end{aligned}$$

which implies that $\lim_{n \rightarrow \infty} d(\mathbf{u}_n, \mathbf{u}_{n+1}) = 0$.

It is easy to observe that $\{\mathbf{u}_n\}$ is Cauchy sequence. As H is complete, so there exists $\mathbf{u} \in H$ such that $\lim_{n \rightarrow \infty} \mathbf{u}_n = \mathbf{u}$.

By continuity of R_μ , we get

$$\mathbf{u} = \lim_{n \rightarrow \infty} \mathbf{u}_{n+1} = \lim_{n \rightarrow \infty} R_\mu \mathbf{u}_n = R_\mu \lim_{n \rightarrow \infty} \mathbf{u}_n = R_\mu \mathbf{u}.$$

Thus, $\mathbf{u}$ is a fixed point of R_μ . Let $\mathbf{m}$ be another fixed point of R_μ such that $\mathbf{u} \neq \mathbf{m}$. Using (2.1)

$$\begin{aligned} d(R_\mu \mathbf{u}, R_\mu \mathbf{m}) &\leq r_1 d(\mathbf{u}, \mathbf{m}) + r_2 \frac{d(\mathbf{u}, R_\mu \mathbf{u}) \cdot d(\mathbf{m}, R_\mu \mathbf{m})}{d(\mathbf{u}, \mathbf{m})} \\ d(\mathbf{u}, \mathbf{m}) &\leq r_1 d(\mathbf{u}, \mathbf{m}). \end{aligned}$$

which is possible only when $d(\mathbf{u}, \mathbf{m}) = 0$. Therefore, R_μ and hence R has unique fixed point.

To prove (iii),

$$\begin{aligned} d(\mathbf{u}_n, \mathbf{u}_{n+1}) &\leq \nu d(\mathbf{u}_{n-1}, \mathbf{u}_n) \\ d(\mathbf{u}_{n+m}, \mathbf{u}_n) &\leq \nu \cdot \frac{1-\nu^m}{1-\nu} d(\mathbf{u}_{n-1}, \mathbf{u}_n) \\ d(\mathbf{u}_{n+m}, \mathbf{u}_n) &\leq \nu^n \cdot \frac{1-\nu^m}{1-\nu} d(\mathbf{u}_0, \mathbf{u}_1). \end{aligned}$$

Letting $m \rightarrow \infty$ in above equations,

$$\begin{aligned} d(u_n, u) &\leq \frac{\nu}{1-\nu} d(u_{n-1}, u_n) \\ d(u_n, u) &\leq \nu^n \cdot \frac{1}{1-\nu} d(u_0, u_1). \end{aligned}$$

Theorem 2.2. *Let (H, d, W) be a complete convex metric space and $R : H \rightarrow H$ be a continuous mapping. Assume that R is an enriched Dass and Gupta contraction map. Then*

- (i) $Fix(R) = u$, for some $u \in H$.
- (ii) The sequence $u_{n+1} = W(u_n, Ru_n, \mu)$, $n \geq 0$, converges to u , for any $u_0 \in H$.
- (iii) The following inequality holds

$$d(u_{n+m}, u) \leq \frac{\nu^n}{1-\nu} d(u_n, u_{n-1}), n, m \geq 1, \quad (2.5)$$

where $\nu = \frac{r_1}{1-r_2}$.

Proof. Theorem 2.1's proof may be used to illustrate this one as well.

3. Enriched Contractions in Convex G -metric Space

In the present section, we first recall some lemmas and definitions from the literature and then introduce the concepts of enriched contractions within the framework of G -metric space.

The following definition and lemma are taken from [12].

Definition 3.1. *Let (H, G) be a G -metric space. A mapping $W : H \times H \times [0, 1] \rightarrow H$ is said to be convex structure on H if for each $u_1, u_2, u_3, u_4 \in H$ and $\mu \in [0, 1]$,*

$$G(u_1, u_2, W(u_3, u_4, \mu)) \leq \mu G(u_1, u_2, u_3) + (1-\mu)G(u_1, u_2, u_4) \quad (3.1)$$

holds. Then the triplet (H, G, W) is called convex G -metric space.

Lemma 3.1. *Let (H, G, W) be a convex G -metric space. If $\mu \in [0, 1]$, then the convex G -metric space is symmetric.*

The following result concerning fixed point sets is recalled from [20].

Lemma 3.2. *Let (H, G, W) be a convex G -metric space and $R : H \rightarrow H$ be a mapping. Define $R_\mu : H \rightarrow H$ as $R_\mu u = W(u, Ru, \mu)$, $u \in H$. Then, for $\mu \in [0, 1]$, $Fix(R) = Fix(R_\mu)$.*

Definition 3.2. *Let (H, G, W) be a convex G -metric space. A mapping $R : H \rightarrow$*

H is said to be an enriched Jaggi type contraction if there exist $r_1, r_2 \geq 0$ and $\mu \in [0, 1)$ such that

$$\begin{aligned} G(W(u_1, Ru_1, \mu), W(u_2, Ru_2, \mu), W(u_2, Ru_2, \mu)) &\leq r_1 G(u_1, u_2, u_2) \\ &+ r_2 \frac{G(u_1, W(u_1, Ru_1, \mu), W(u_1, Ru_1, \mu)) \cdot G(u_2, W(u_2, Ru_2, \mu), W(u_2, Ru_2, \mu))}{G(u_1, u_2, u_2)} \end{aligned} \quad (3.2)$$

for all distinct $u_1, u_2 \in H$ and $r_1 + r_2 < 1$.

Definition 3.3. Let (H, G, W) be a convex G -metric space. A mapping $R : H \rightarrow H$ is said to be an enriched Dass and Gupta type contraction if there exist $r_1, r_2 \geq 0$ and $\mu \in [0, 1)$ such that

$$\begin{aligned} G(W(u_1, Ru_1, \mu), W(u_2, Ru_2, \mu), W(u_2, Ru_2, \mu)) &\leq r_1 G(u_1, u_2, u_2) \\ &+ r_2 \frac{G(u_2, W(u_2, Ru_2, \mu), W(u_2, Ru_2, \mu)) \cdot (1 + G(u_1, W(u_1, Ru_1, \mu), W(u_1, Ru_1, \mu)))}{(1 + G(u_1, u_2, u_2))} \end{aligned} \quad (3.3)$$

for all distinct $u_1, u_2 \in H$ and $r_1 + r_2 < 1$.

Theorem 3.1. Let (H, G, W) be a complete convex G -metric space and $R : H \rightarrow H$ be a continuous mapping. Assume that R is an enriched Jaggi type contraction map. Then

- (i) $\text{Fix}(R) = u$, for some $u \in H$.
- (ii) The sequence $u_{n+1} = W(u_n, Ru_n, \mu)$, $n \geq 0$, converges to u , for any $u_0 \in H$.

Proof. By (3.2), we have $R_\mu : H \rightarrow H$ such that

$$G(R_\mu u_1, R_\mu u_2, R_\mu u_2) \leq r_1 G(u_1, u_2, u_2) + r_2 \frac{G(u_1, R_\mu u_1, R_\mu u_1) \cdot G(u_2, R_\mu u_2, R_\mu u_2)}{G(u_1, u_2, u_2)}, \quad (3.4)$$

which implies that R_μ is an enriched Jaggi type contraction. Define $R_\mu u_n = u_{n+1}$, such that $u_n \neq u_{n+1}$, $\forall n \geq 0$.

Let $u_1 = u_{n-1}$ and $u_2 = u_n$ in (3.2) to get

$$\begin{aligned} G(u_n, u_{n+1}, u_{n+1}) &\leq r_1 G(u_{n-1}, u_n, u_n) + r_2 \frac{G(u_{n-1}, u_n, u_n) \cdot G(u_n, u_{n+1}, u_{n+1})}{G(u_{n-1}, u_n, u_n)} \\ &= r_1 G(u_{n-1}, u_n, u_n) + r_2 G(u_n, u_{n+1}, u_{n+1}) \\ G(u_n, u_{n+1}, u_{n+1}) &\leq \frac{r_1}{1 - r_2} G(u_{n-1}, u_n, u_n) \end{aligned}$$

$$\begin{aligned}
 &= \nu G(\mathbf{u}_{n-1}, \mathbf{u}_n, \mathbf{u}_n) \left(\text{where } \nu = \frac{r_1}{1 - r_2} \right) \\
 G(\mathbf{u}_n, \mathbf{u}_{n+1}, \mathbf{u}_{n+1}) &\leq \nu^n G(\mathbf{u}_0, \mathbf{u}_1, \mathbf{u}_1).
 \end{aligned}$$

which implies that $\lim_{n \rightarrow \infty} G(\mathbf{u}_n, \mathbf{u}_{n+1}, \mathbf{u}_{n+1}) = 0$.

It is easy to observe that $\{\mathbf{u}_n\}$ is a Cauchy sequence. As G is complete, so there exists $\mathbf{u} \in G$ such that $\lim_{n \rightarrow \infty} \mathbf{u}_n = \mathbf{u}$.

Due to the continuity of R and W , we get

$$\mathbf{u} = \lim_{n \rightarrow \infty} \mathbf{u}_{n+1} = \lim_{n \rightarrow \infty} R_\mu \mathbf{u}_n = R_\mu \lim_{n \rightarrow \infty} \mathbf{u}_n = R_\mu \mathbf{u}.$$

Thus, $\mathbf{u}$ is a fixed point of R_μ . Let $\mathbf{m}$ be another fixed point of R_μ such that $\mathbf{u} \neq \mathbf{m}$. Using (3.2)

$$\begin{aligned}
 G(R_\mu \mathbf{u}, R_\mu \mathbf{m}, R_\mu \mathbf{m}) &\leq r_1 G(\mathbf{u}, \mathbf{m}, \mathbf{m}) + r_2 \frac{G(\mathbf{u}, R_\mu \mathbf{u}, R_\mu \mathbf{u}).G(\mathbf{m}, R_\mu \mathbf{m}, R_\mu \mathbf{m})}{G(\mathbf{u}, \mathbf{m}, \mathbf{m})} \\
 G(\mathbf{u}, \mathbf{m}, \mathbf{m}) &\leq r_1 G(\mathbf{u}, \mathbf{m}, \mathbf{m}).
 \end{aligned}$$

Therefore, R_μ and hence R has a unique fixed point.

Theorem 3.2. *Let (H, G, W) be a complete convex G -metric space and $R : H \rightarrow H$ be a continuous mapping. Assume that R is an enriched Dass and Gupta type contraction map. Then*

- (i) $\text{Fix}(R) = \mathbf{u}$, for some $\mathbf{u} \in H$.
- (ii) The sequence $\mathbf{u}_{n+1} = W(\mathbf{u}_n, R\mathbf{u}_n, \mu)$, $n \geq 0$, converges to $\mathbf{u}$, for any $\mathbf{u}_0 \in H$.

Proof. The proof of Theorem 3.1 may also be used to demonstrate this one.

4. Consequences

The important outcome of [6] is the following Consequence.

Corollary 4.1. *Let (H, d, W) be a complete convex metric space and $R : H \rightarrow H$ be a continuous mapping. Assume that $d(R_\mu \mathbf{u}_1, R_\mu \mathbf{u}_2) \leq r_1 d(\mathbf{u}_1, \mathbf{u}_2)$. Then*

- (i) $\text{Fix}(R) = \mathbf{u}$, for some $\mathbf{u} \in H$.
- (ii) The sequence $\mathbf{u}_{n+1} = W(\mathbf{u}_n, R\mathbf{u}_n, \mu)$, $n \geq 0$, converges to $\mathbf{u}$, for any $\mathbf{u}_0 \in H$.
- (iii) The following inequality holds

$$d(\mathbf{u}_{n+m}, \mathbf{u}) \leq \frac{\nu^n}{1 - \nu} d(\mathbf{u}_n, \mathbf{u}_{n-1}), n, m \geq 1, \quad (4.1)$$

where $\nu = \frac{r_1}{1 - r_2}$.

Corollary 4.2. [2] Let (H, d) be a complete metric space. If $R : H \rightarrow H$ is Banach contraction mapping. Then R has a unique fixed point.

Corollary 4.3. [11] Let (H, d) be a complete metric space. If $R : H \rightarrow H$ is Jaggi contraction mapping. Then R has a unique fixed point.

Corollary 4.4. [8] Let (H, d) be a complete metric space. If $R : H \rightarrow H$ is Dass and Gupta contraction mapping. Then R has a unique fixed point.

Example 4.1. Let $H : \mathbb{R} \rightarrow \mathbb{R}$ be a mapping defined as $Hu = 1 - \frac{5}{2}u$, $u \in \mathbb{R}$.

Define $W(u_1, u_2, \mu) = \mu u_1 + (1 - \mu)u_2$ with $\mu = \frac{1}{2}$ and $d(u_1, u_2) = |u_1 - u_2|$.

$$\begin{aligned} d(W(u_1, Hu_1, \mu), W(u_2, Hu_2, \mu)) &= |W(u_1, Hu_1, \mu) - W(u_2, Hu_2, \mu)| = \frac{3}{4}|u_1 - u_2| \\ &\leq \frac{3}{4}|u_1 - u_2| + \frac{1}{8} \frac{d(u_1, W(u_1, Hu_1, \mu)).d(u_2, W(u_2, Hu_2, \mu))}{d(u_1, u_2)} \\ &= \frac{3}{4}d(u_1, u_2) + \frac{1}{8} \frac{d(u_1, W(u_1, Hu_1, \mu)).d(u_2, W(u_2, Hu_2, \mu))}{d(u_1, u_2)}. \end{aligned}$$

Thus, H is an enriched Jaggi contraction with $r_1 = \frac{3}{4}$ and $r_2 = \frac{1}{8}$.

Now, by assuming $u_1 = 0$ and $u_2 = \frac{2}{7}$. $d(Hu_1, Hu_2) = \frac{5}{7}$ and

$$r_1 d(u_1, u_2) + r_2 \frac{d(u_1, Hu_1).d(u_2, Hu_2)}{d(u_1, u_2)} = \frac{2}{7}r_1 < \frac{2}{7}.$$

Hence H is not a Jaggi contraction.

Similarly, H is an enriched Dass and Gupta contraction, but H is not a Dass and Gupta contraction.

H is also an enriched contraction. As,

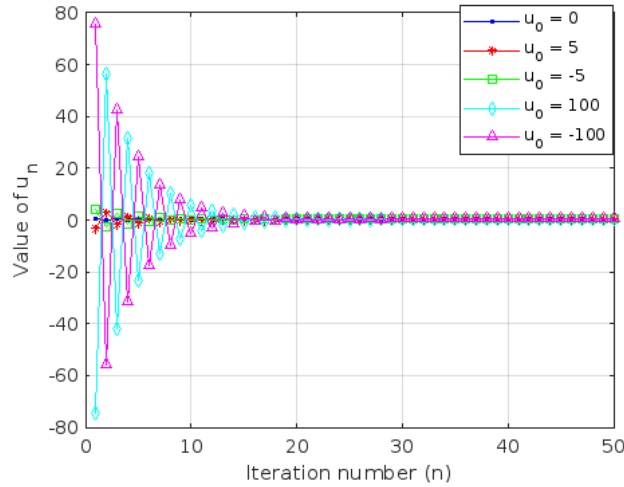
$$d(W(u_1, Hu_1, \mu), W(u_2, Hu_2, \mu)) = \frac{3}{4}|u_1 - u_2| \leq r_1 d(u_1, u_2), \text{ for } r_1 = \left[\frac{3}{4}, 1 \right).$$

But, H is not a Banach contraction. Because, $d(Hu_1, Hu_2) = \frac{5}{2}|u_1 - u_2| \geq d(u_1, u_2)$.

The following table represents some values of $\{u_n\}$ with different initial guess.

Few values of $\{u_n\}$					
n	$\{u_n\}$				
	Case 1	Case 2	Case 3	Case 4	Case 5
	0	5	-5	100	-100
1	0.500000	-3.250000	4.250000	-74.500000	75.500000
2	0.125000	2.937500	-2.687500	56.375000	-56.125000
3	0.406250	-1.703125	2.515625	-41.781250	42.593750
4	0.195312	1.777343	-1.386718	31.835937	-31.445312
5	0.353515	-0.833007	1.540039	-23.376953	24.083984
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
46	0.285713	0.285722	0.285704	0.285892	0.285534
47	0.285714	0.285707	0.285721	0.285580	0.285848
48	0.285713	0.285719	0.285708	0.285814	0.285613
49	0.285714	0.285710	0.285718	0.285638	0.285790
50	0.285714	0.285716	0.285711	0.285770	0.285657

The following figure presents convergence behavior of $\{u_n\}$ with different starting points.



5. Conclusion

The research successfully achieves its goal of establishing FP theorems for enriched Jaggi contractions and enriched Dass and Gupta contractions in convex metric space. It is shown that these contractions have a unique fixed point, which

can be approximated using a suitable Kransoselskij iterative technique. These findings are significant because they contribute to the existing body of knowledge in fixed-point theory. The extension of enriched contractions to the convex G -metric space has expanded the applicability of these theorems.

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