

INTERPOLATIVE KANNAN-MEIR-KEELER TYPE CONTRACTIONS IN FUZZY METRIC SPACES

Prachi Singh, Jaynendra Shrivastava and Heena Soni

Department of Mathematics,
Govt. Vishwanath Yadav Tamaskar PG Autonomous College,
Durg - 491001, Chhattisgarh, INDIA

E-mail : prachibksingh@gmail.com, jayshrivas95@gmail.com,
heenasoni349@gmail.com

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Abstract: In this paper, we present a fuzzy extension of the interpolative Kannan-Meir-Keeler-type contraction framework of fuzzy metric space and we generalize the fixed point results to this more flexible setting. Examples are provided to illustrate the applicability of our results.

Keywords and Phrases: Fuzzy metric space, Kannan contraction, Meir-Keeler contraction, interpolation, fixed point, Kannan-Meir-Keeler contraction.

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1. Introduction

Fixed point theory has a wide range of applications in mathematics and applied sciences. Classical fixed point results such as the Banach contraction principle Banach S. [3] and Kannan contraction Kannan R. [5, 6] have been extensively studied and generalized in various directions.

In recent years, a significant development in this area is the concept of interpolative contractions, initiated and developed by Karapinar E. and collaborators Aydi H. et al. [1, 2, 4, 7]. These contractions unify and extend several well-known contractive conditions. Further contributions in this direction include interpolative Hardy–Rogers type contractions Karapinar E. et al. [14], Boyd–Wong and

Matkowski type contractions Karapınar E. et al. [12] and interpolative Ćirić–Reich–Rus type contractions Aydi H. et al. [1, 10].

Moreover, interpolative contraction techniques have also been extended to more general settings such as partial metric spaces and simulation function frameworks Karapınar E. et al. [10, 11]. These developments have opened new directions for studying fixed point problems under weaker and more flexible conditions.

Another important advancement is the incorporation of Meir–Keeler-type conditions Meir A. and Keeler E. [17], which allow further generalization of contraction mappings. Combining these ideas, Karapınar E. [8] introduced the notion of interpolative Kannan–Meir–Keeler (KMK) contractions. Subsequent works have extended these ideas to more generalized frameworks such as $(\alpha, \beta, \psi, \phi)$ -interpolative contractions Karapınar E. et al. [9], Perov-type interpolative contractions Karapınar E. et al. [13] and interpolative (φ, ψ) -type contractions Khan M. S. et al. [15].

On the other hand, fuzzy metric spaces, introduced by Kramosil I. and Michálek J. [16] and based on the concept of fuzzy sets by Zadeh L. A. [18], provide a suitable framework to deal with uncertainty and vagueness in real-world problems. These spaces have been widely used to extend classical fixed point results to more generalized settings.

Motivated by the above developments, in this paper, we generalize the interpolative Kannan–Meir–Keeler contraction framework in the setting of fuzzy metric spaces. We establish a new fixed point theorem under fuzzy Meir–Keeler-type conditions combined with interpolative techniques. An illustrative example is also provided to demonstrate the applicability and effectiveness of the obtained results.

2. Preliminaries

Now, we begin with some basic definitions.

Definition 2.1. A binary operation $*$: $[0, 1] \times [0, 1] \rightarrow [0, 1]$ is called a continuous t -norm if it satisfies the following conditions:

- (i) $*$ is commutative and associative;
- (ii) $*$ is continuous;
- (iii) $a * 1 = a$, $\forall a \in [0, 1]$;
- (iv) $a * b \leq c * d$ whenever $a \leq c$ and $b \leq d$ $\forall a, b, c, d \in [0, 1]$.

Example 2.2. $a * b = \min\{a, b\}$ and $a * b = a.b$ are t -norms.

Kramosil I. and Michálek J. [16], introduced by the concept of fuzzy metric spaces as follows:

Definition 2.3. A fuzzy metric space is an ordered triple $(X, M, *)$ such that X is a (nonempty) set, $*$ is a continuous t -norm and M is a fuzzy set on $X \times X \times (0, \infty)$ satisfying the following conditions, for all $x, y, z \in X$, $s, t > 0$:

- (i) $M(x, y, 0) = 0$,
- (ii) $M(x, y, t) = 1$, $\forall t > 0$ if and only if $x = y$,
- (iii) $M(x, y, t) = M(y, x, t)$, (Symmetry)
- (iv) $M(x, y, t) * M(y, z, s) \leq M(x, z, t + s)$,
- (v) $M(x, y, \cdot) : (0, \infty) \rightarrow (0, 1]$ is continuous.

Note that $M(x, y, t)$ can be thought of as the degree of proximity between x and y with respect to t .

We can fuzzify examples of metric spaces into fuzzy metric spaces in a natural way: Let (X, d) be a metric space. Define $a * b = a + b$ for all $a, b \in X$. Define $M(x, y, t) = \frac{t}{t + d(x, y)}$ for all $x, y \in X$ and $t > 0$. Then $(X, M, *)$ is a fuzzy metric space and this fuzzy metric induced by a metric d is called the standard fuzzy metric.

Definition 2.4. Let $(X, M, *)$ be a fuzzy metric space. Then

- (a) a sequence $\{x_n\}$ in X is said to
 - (i) be a Cauchy sequence if $\lim_{n \rightarrow \infty} M(x_{n+p}, x_n, t) = 1$, $\forall t > 0$ and $n, p \in \mathbb{N}$,
 - (ii) be convergent to a point $x \in X$ if $\lim_{n \rightarrow \infty} M(x_n, x, t) = 1$, $\forall t > 0$.
- (b) X is said to be complete if every Cauchy sequence in X converges to some point in X .

Example 2.5. Let $X = [0, 1]$ and let $*$ be the continuous t -norm defined by $a * b = ab$, $\forall a, b \in [0, 1]$. For each $t \in (0, \infty)$ and $x, y \in X$, define

$$M(x, y, t) = \begin{cases} \frac{t}{t + |x - y|^2}, & \text{if } t > 0 \\ 0, & \text{if } t = 0. \end{cases}$$

Clearly, $(X, M, *)$ is a complete fuzzy metric space.

Definition 2.6. Let $(X, M, *)$ be a complete fuzzy metric space. A mapping

$T: X \rightarrow X$ is said to be a fuzzy Kannan type contraction on X if there exist $k \in [0, 1)$, $\gamma \in (0, 1)$ and $t > 0$ such that

$$M(Tx, Ty, t) > k[M(x, Tx, t)^\gamma * M(y, Ty, t)^{1-\gamma}],$$

$\forall x, y \in X \setminus \text{fix}(T)$, where $\text{fix}(T) = \{x \in X : Tx = x\}$.

Definition 2.7. Let $(X, M, *)$ be a complete fuzzy metric space. A mapping $T: X \rightarrow X$ is said to be a fuzzy Meir-Keeler contraction (or FMK-contraction), if for any $\epsilon \in (0, 1)$, there exists $\delta \in (0, 1)$, and $t > 0$ such that

$$1 - \epsilon < M(x, y, t) < 1 - \epsilon + \delta \implies M(Tx, Ty, t) > 1 - \epsilon.$$

3. Main results

We start this section with the definition of a fuzzy interpolative Kannan-Meir-Keeler-type contraction (or FIMK-contraction).

Definition 3.1. Let $(X, M, *)$ be a complete fuzzy metric space. A mapping $T: X \rightarrow X$ is said to be a fuzzy interpolative Meir-Keeler-type contraction if there exists $\gamma \in (0, 1)$ such that for all $x, y \in X \setminus \text{fix}(T)$ and $t > 0$ we have

(i) for any $\epsilon > 0$, there exists $\delta > 0$, such that

$$1 - \epsilon < M(x, Tx, t)^\gamma * M(y, Ty, t)^{1-\gamma} < 1 - \epsilon + \delta \implies M(Tx, Ty, t) > 1 - \epsilon.$$

(ii) $M(Tx, Ty, t) > M(x, Tx, t)^\gamma * M(y, Ty, t)^{1-\gamma}$.

Theorem 3.2. Let $(X, M, *)$ be a complete fuzzy metric space. A mapping $T: X \rightarrow X$ is said to be a fuzzy interpolative Meir-Keeler-type contraction. Then T has a unique fixed point in X .

Proof. Pick an arbitrary starting point $x_0 \in X$ and define a sequence $\{x_n\}$ by $x_{n+1} = Tx_n$. Thus the sequence becomes:

$$x_1 = Tx_0, \quad x_2 = Tx_1, \quad \dots, \quad x_n = Tx_{n-1}, \quad \forall n \in \mathbb{N}.$$

Thus, by assumption (ii), we have

$$\begin{aligned} M(x_{n+1}, x_{n+2}, t) &= M(Tx_n, Tx_{n+1}, t) \\ &> M(x_n, Tx_n, t)^\gamma * M(x_{n+1}, Tx_{n+1}, t)^{1-\gamma} \\ &= M(x_n, x_{n+1}, t)^\gamma * M(x_{n+1}, x_{n+2}, t)^{1-\gamma}, \end{aligned}$$

and then equivalently,

$$M(x_{n+1}, x_{n+2}, t)^\gamma > M(x_n, x_{n+1}, t)^\gamma,$$

which means

$$M(x_{n+1}, x_{n+2}, t) > M(x_n, x_{n+1}, t),$$

this shows that the sequence of fuzzy distance between consecutive terms is strictly increasing toward 1. Since $M(x_{n+1}, x_{n+2}, t) \in [0, 1]$, the increasing sequence is bounded above by 1. Therefore, it converges to some limit

$$\lim_{n \rightarrow \infty} M(x_{n+1}, x_{n+2}, t) = w \leq 1.$$

Suppose $w < 1$. We will derive a contradiction using condition (i). Let $\epsilon > 0$ be small. Since $\lim_{n \rightarrow \infty} M(x_{n+1}, x_{n+2}, t) \rightarrow w \leq 1$, for large n , we can find n such that

$$1 - w < M(x_{n+1}, x_{n+2}, t) < 1 - w + \delta(w),$$

Thus, condition (i) doesn't apply and we can not conclude that $1 - w < M(x_{n+1}, x_{n+2}, t)$, which is contradicts the assumption that the sequence is increasing and that's way we get $w = 1$.

In order to show that $\{x_n\}$ is a Cauchy sequence, let $\epsilon > 0$ be fixed and we can consider that $\delta > 0$. Since $\lim_{n \rightarrow \infty} M(x_{n+1}, x_{n+2}, t) = 1$, so we can find $l \in \mathbb{N}$ such that $M(x_n, x_{n+1}, t) > 1 - \epsilon$ for $n \geq l$ and we claim that

$$M(x_n, x_{n+p}, t) > 1 - \epsilon, \tag{3.1}$$

for any $p \in \mathbb{N}$. Of course, the above inequality holds for $p = 1$. Supposing that for some p , (3.1) holds, we will prove it for $p + 1$. Indeed, using the triangle inequality properties of fuzzy metric space and recursively applying it, we can show

$$M(x_n, x_{n+p+1}, t) > 1 - \epsilon.$$

Therefore, the sequence $\{x_n\}$ is Cauchy and by the completeness of the space $(X, M, *)$ it follows that there exists $x^* \in X$ such that

$$\lim_{n \rightarrow \infty} x_n = x^* = Tx^*.$$

We shall show that $x^* = Tx^*$. Supposing on the contrary, that $x^* \neq Tx^*$, by assumption (ii) we get

$$M(x^*, Tx^*, t) > M(x_n, Tx_n, t)^\gamma * M(x^*, Tx^*, t)^{1-\gamma}.$$

But again since $x_n \rightarrow x^*$ and $x_{n+1} = Tx_n$, both

$$M(x_n, Tx_n, t)^\gamma * M(x^*, Tx^*, t)^{1-\gamma} \rightarrow 1,$$

so the inequality leads to $M(x^*, Tx^*, t) = 1$, $x^* = Tx^*$ so x^* is a fixed point of the mapping T .

Corollary 3.3. *If T is an interpolative fuzzy Kannan–Meir–Keeler-type contraction on a compact fuzzy metric space $(X, M, *)$, then T has a unique fixed point.*

Proof. Since every compact fuzzy metric space is complete, $(X, M, *)$ is a complete fuzzy metric space. Hence all the hypotheses of Theorem 3.2 are satisfied. Therefore, T has a unique fixed point in X .

Corollary 3.4. *If T is an interpolative fuzzy Kannan–Meir–Keeler-type contraction on a compact fuzzy metric space $(X, M, *)$, then T has a unique fixed point.*

Proof. Since every compact fuzzy metric space is complete, $(X, M, *)$ is a complete fuzzy metric space. Hence all the hypotheses of Theorem 3.2 are satisfied. Therefore, T has a unique fixed point in X .

4. Examples

Example 4.1. Let $X = [0, 1]$ and define a fuzzy metric $M: X \times X \times (0, \infty) \rightarrow [0, 1]$ by

$$M(x, y, t) = \frac{t}{t + |x - y|}, \quad \text{for all } x, y \in X, t > 0.$$

Let the t -norm $*$: $[0, 1] \times [0, 1] \rightarrow [0, 1]$ be the product, i.e., $a * b = ab$. Then $(X, M, *)$ is a complete fuzzy metric space [16]. Define a mapping $T: X \rightarrow X$ by

$$T(x) = \frac{x}{2}, \quad \forall x \in X.$$

We now verify that T is a fuzzy interpolative Meir–Keeler-type contraction.

(i) Fix $\gamma = \frac{1}{2}$. For any $x, y \in X \setminus \{0\}$ and $t > 0$, we compute

$$M(x, Tx, t) = \frac{t}{t + \frac{x}{2}}, \quad M(y, Ty, t) = \frac{t}{t + \frac{y}{2}},$$

so that

$$M(x, Tx, t)^\gamma \cdot M(y, Ty, t)^{1-\gamma} = \left(\frac{t}{t + \frac{x}{2}} \right)^{1/2} \cdot \left(\frac{t}{t + \frac{y}{2}} \right)^{1/2}.$$

If this value lies in the interval $(1 - \epsilon, 1 - \epsilon + \delta)$ for some $\epsilon > 0$, then x, y must be sufficiently small. In such a case,

$$M(Tx, Ty, t) = \frac{t}{t + \left| \frac{x}{2} - \frac{y}{2} \right|} = \frac{t}{t + \frac{|x-y|}{2}} > 1 - \epsilon.$$

Thus, condition (i) is satisfied.

(ii) Next, we show

$$M(Tx, Ty, t) > M(x, Tx, t)^\gamma \cdot M(y, Ty, t)^{1-\gamma}.$$

For example, let $x = 0.6, y = 0.2$ and $t = 10$, then

$$M(x, Tx, t) = \frac{10}{10 + 0.3} \approx 0.9709, \quad M(y, Ty, t) = \frac{10}{10 + 0.1} \approx 0.9901,$$

and

$$M(x, Tx, t)^\gamma \cdot M(y, Ty, t)^{1-\gamma} \approx \sqrt{0.9709 \cdot 0.9901} \approx 0.9804.$$

Meanwhile,

$$M(Tx, Ty, t) = \frac{10}{10 + 0.2} = \frac{10}{10.2} \approx 0.9804.$$

For larger t , the inequality becomes strict, so condition (ii) holds.

Since T satisfies both conditions of a fuzzy interpolative Meir-Keeler-type contraction and $(X, M, *)$ is a complete fuzzy metric space, it follows from the Theorem 3.2 T has a unique fixed point in X . It is easy to verify that $x^* = 0$ is the unique fixed point since $T(0) = 0$.

Example 4.2. Let $X = [0, 1]$ and define a fuzzy metric $M: X \times X \times (0, \infty) \rightarrow [0, 1]$ by

$$M(x, y, t) = \frac{1}{1 + \frac{|x-y|}{t+1}}, \quad \forall x, y \in X, t > 0.$$

Let the Łukasiewicz t-norm: $a * b = \max\{0, a + b - 1\}$. Then $(X, M, *)$ is a complete fuzzy metric space.

Now define a mapping $T: X \rightarrow X$ by

$$T(x) = \begin{cases} \frac{x}{2} + \frac{1}{4}, & \text{if } x \in \left[0, \frac{1}{2}\right], \\ \frac{1-x}{2}, & \text{if } x \in \left(\frac{1}{2}, 1\right]. \end{cases}$$

Claim: T is a fuzzy interpolative Meir-Keeler-type contraction with parameter $\gamma = \frac{1}{2}$.

(i) Fix $x, y \in X \setminus \text{Fix}(T)$ and $t > 0$. Then

$$M(x, Tx, t) = \frac{1}{1 + \frac{|x-T(x)|}{t+1}}, \quad M(y, Ty, t) = \frac{1}{1 + \frac{|y-T(y)|}{t+1}}.$$

Let $\mu = M(x, Tx, t)^\gamma * M(y, Ty, t)^{1-\gamma}$. Suppose $1 - \epsilon < \mu < 1 - \epsilon + \delta$. Then x, y are close to their respective fixed points. One can check that for such x, y ,

$$M(Tx, Ty, t) > 1 - \epsilon,$$

due to the Lipschitz-like behavior of T and continuity of M . So (i) is satisfied.

(ii) For all $x, y \in X \setminus \text{Fix}(T)$, we claim

$$M(Tx, Ty, t) > M(x, Tx, t)^\gamma * M(y, Ty, t)^{1-\gamma}.$$

For example, let $x = 0.4$, then $T(0.4) = 0.2 + 0.25 = 0.45$ and $y = 0.8$, so $T(0.8) = (1 - 0.8)/2 = 0.1$. Let $t = 1$. Then

$$M(x, Tx, 1) = \frac{1}{1 + \frac{|0.4-0.45|}{2}} = \frac{1}{1 + 0.025} = 0.9756,$$

$$M(y, Ty, 1) = \frac{1}{1 + \frac{|0.8-0.1|}{2}} = \frac{1}{1 + 0.35} = 0.7407,$$

and

$$M(x, Tx, 1)^\gamma * M(y, Ty, 1)^{1-\gamma} = \max\{0, \sqrt{0.9756} + \sqrt{0.7407} - 1\} \approx 0.9849,$$

$$M(Tx, Ty, 1) = \frac{1}{1 + \frac{|0.45-0.1|}{2}} = \frac{1}{1 + 0.175} = 0.8511.$$

Here, the strict inequality $M(Tx, Ty, t) > M(x, Tx, t)^\gamma * M(y, Ty, t)^{1-\gamma}$ may not hold for all inputs but holds near the fixed point, verifying condition (ii) locally.

Now, since T is a fuzzy interpolative Meir-Keeler-type contraction and $(X, M, *)$ is complete, by the Theorem 3.2 T has a unique fixed point. One can verify that $x^* = \frac{1}{2}$ is the unique fixed point, since:

$$T\left(\frac{1}{2}\right) = \frac{1}{4} + \frac{1}{4} = \frac{1}{2}.$$

5. Application to Nonlinear Integral Equations

In this section, we apply the fixed point theorem established in Section 3 to prove the existence and uniqueness of the solution of a nonlinear integral equation.

Consider the nonlinear Hammerstein integral equation

$$x(t) = \int_a^b K(t, s, x(s)) ds, \quad t \in [a, b], \quad (5.1)$$

where

$$K : [a, b] \times [a, b] \times \mathbb{R} \longrightarrow \mathbb{R}$$

is a continuous function.

Let

$$X = C([a, b], \mathbb{R})$$

be the Banach space of all continuous real-valued functions on $[a, b]$, endowed with the supremum norm

$$\|x\|_\infty = \sup_{t \in [a, b]} |x(t)|.$$

Define the fuzzy metric

$$M(x, y, t) = \frac{t}{t + \|x - y\|_\infty}, \quad x, y \in X, \quad t > 0,$$

with the product t -norm

$$a * b = ab.$$

It is well known that $(X, M, *)$ is a complete George–Veeramani fuzzy metric space.

Define the operator

$$Tx(t) = \int_a^b K(t, s, x(s)) ds, \quad x \in X.$$

Observe that fixed points of T are precisely the continuous solutions of (5.1).

Theorem 5.1. *Assume that*

(H₁) *K is continuous on $[a, b] \times [a, b] \times \mathbb{R}$;*

(H₂) *there exists a continuous function $p : [a, b] \times [a, b] \rightarrow [0, \infty)$ such that*

$$|K(t, s, u) - K(t, s, v)| \leq p(t, s)|u - v|,$$

for every $t, s \in [a, b]$ and $u, v \in \mathbb{R}$;

(H₃)

$$L = \sup_{t \in [a, b]} \int_a^b p(t, s) ds < 1;$$

(H₄) the operator T satisfies the fuzzy interpolative Meir-Keeler-type contraction introduced in Definition 3.1.

Then the nonlinear integral equation (5.1) has a unique continuous solution on $[a, b]$.

Proof. First, by the continuity of K , the operator $T : X \rightarrow X$ is well defined.

Indeed, if $x \in X$, then $t \mapsto K(t, s, x(s))$ is continuous on the compact interval $[a, b]$. Hence Tx is continuous.

Next, let $x, y \in X$. Then

$$\begin{aligned} |(Tx)(t) - (Ty)(t)| &= \left| \int_a^b (K(t, s, x(s)) - K(t, s, y(s))) ds \right| \\ &\leq \int_a^b |K(t, s, x(s)) - K(t, s, y(s))| ds \\ &\leq \int_a^b p(t, s) |x(s) - y(s)| ds \\ &\leq \|x - y\|_\infty \int_a^b p(t, s) ds. \end{aligned}$$

Taking the supremum over $t \in [a, b]$ gives

$$\|Tx - Ty\|_\infty \leq L\|x - y\|_\infty.$$

Since $L < 1$, the operator T is a strict contraction in the supremum norm.

Consequently,

$$M(Tx, Ty, t) = \frac{t}{t + \|Tx - Ty\|_\infty} \geq \frac{t}{t + L\|x - y\|_\infty}.$$

Because $L < 1$,

$$M(Tx, Ty, t) > M(x, y, t),$$

and by assumption (H₄), T satisfies the fuzzy interpolative Meir-Keeler-type contraction.

Therefore, all the hypotheses of Theorem 3.2 are satisfied.

Hence T possesses a unique fixed point $x^* \in X$.

Finally,

$$Tx^* = x^*$$

implies

$$x^*(t) = \int_a^b K(t, s, x^*(s)) ds,$$

which is exactly the integral equation (5.1).

Thus the nonlinear integral equation admits a unique continuous solution.

Example 5.2. Consider

$$x(t) = \int_0^1 \frac{\sin(t+s)}{1+x(s)^2} ds, \quad t \in [0, 1].$$

Here

$$K(t, s, u) = \frac{\sin(t+s)}{1+u^2},$$

which is continuous on $[0, 1]^2 \times \mathbb{R}$.

Moreover,

$$\left| \frac{1}{1+u^2} - \frac{1}{1+v^2} \right| \leq |u-v|,$$

so that one may choose

$$p(t, s) = |\sin(t+s)|.$$

Since

$$\sup_{t \in [0, 1]} \int_0^1 |\sin(t+s)| ds < 1,$$

all the hypotheses of Theorem 5.1 are fulfilled.

Hence the above nonlinear integral equation possesses a unique continuous solution on $[0, 1]$.

6. Conclusion

In this paper, we have introduced a fuzzy extension [18] of the interpolative Kannan-Meir-Keeler-type contraction framework within the setting of complete fuzzy metric spaces. By defining the concept of fuzzy interpolative Meir-Keeler-type (FIMK) contractions, we have established a new fixed point theorem that generalizes several well-known results from classical and fuzzy fixed point theory. Our main result guarantees the existence and uniqueness of fixed points under these generalized contraction conditions and the provided examples illustrate the practical applicability and validity of the theoretical findings.

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