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A Common Fixed Point Theorem for Self Mappings for Compatible Mappings of Type (E) in Fuzzy Metric space

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Abstract

The aim of this paper is to obtain a common fixed point theorem for self mappings in complete fuzzy metric space by compactable of type (E). Our result generalizes and improves other similar results in literature [7].

Mathematics Subject Classification: 47H10, 54H25 Keywords: fuzzy metric space, fixed point, compatible of type (E)

1. Introduction:

Fixed point theory is an important area of functional analysis. The study of common fixed point of mappings satisfying contractive type conditions has been a very active field of research. In 1965, the concept of fuzzy set was introduced by L.A Zadeh [9]. Then, in 1975, O. Kramosil and J. Michalek introduced the fuzzy metric space as a generalization of metric space. In 1994, George and Veeramani [1] modified the notion of fuzzy metric spaces with the help of continuous t-norms. In 1986, G. Jungck [5] introduced notion of compatible mappings in metric space. In 2000, B. Singh and M.S. Chouhan [20] introduced the concept of compatible mappings in fuzzy metric space. In 1993, G. Jungck, P. P. Murthy and Y. J. Cho [4] gave a generalization of compatible mappings called compatible mappings of type (A) which is equivalent to the concept of compatible mappings under some conditions. In 1994, H. K. Pathak, Y. J. Cho, S. S. Chang and S. M. Kang [6] introduced the concept of compatible mappings of type (P) and compared with compatible mappings of type (A) and compatible mappings. In 1998, R. P. Pant [15] introduced the notion of reciprocal continuity of mappings in metric space. In 1999, R. Vasuki [16] introduced the notion pointwise R-weakly commuting mappings in fuzzy metric space. Recently, in 2007, M.R. Singh and Y. M. Singh [10] introduced the concept of compatible mappings of type (E) in metric space. Since then, many authors have obtained fixed point theorems in fuzzy metric space using these compatible notions. The purpose of this paper is to establish a common fixed point theorem for compatible mappings of type (E) [7] in fuzzy metric spaces with example

2. Preliminaries:

We start with the following definitions.

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

(a) $*$ is commutative and associative;

(b) $*$ is continuous;

(c) $a * 1 = a$ for all $a \in [0, 1]$; and

(d) $a * b \leq c * d$ whenever $a \leq c$ and $b \leq d$, and $a, b, c, d \in [0, 1]$.

Definition 2.2 [1] A 3-tuple $(X, M, *)$ is said to be a fuzzy metric space if X is an arbitrary set, $*$ is a continuous t-norm and M is a fuzzy set on $X^2 \times (0, \infty)$ satisfying the following conditions: for all $x, y, z \in X$ and $s, t > 0$,

(FM1) $M(x, y, t) > 0$;

(FM 2) $M(x, y, t) = 1$ if and only if $x = y$;

(FM 3) $M(x, y, t) = M(y, x, t)$;

(FM 4) $M(x, y, t) * M(y, z, s) \leq M(x, z, t + s)$; and

(FM 5) $M(x, y, .): (0,\infty) \to (0, 1]$ is continuous.

Then M is called a fuzzy metric on X. The function $M(x, y, t)$ denote the degree of nearness between x and y with respect to t. Also, we consider the following condition in the fuzzy metric spaces $(X, M, *)$.

(FM6) $\lim_{t\to\infty} M(x, y, t) = 1$, for all $x, y \in X$.

Example 2.1[1]: Let (X, d) be a metric space. Denote $a * b = ab$ for all $a, b \in [0, 1]$ and let M be fuzzy sets on $X^2 \times (0, \infty)$ defined as follows: $M(x, y, t) = \frac{t}{t+d(x,y)}$, for all x, y in X. Then $(X, M, *)$ is a fuzzy metric space. This fuzzy metric is the standard fuzzy metric space induced by a metric d.

Definition 2.3 [1] Let $(X, M, *)$ be a fuzzy metric space. Then

(i) a sequence $\{x_n\}$ in X is said to be convergent to a point x_0 in X if for each $\varepsilon > 0$ and each $t > 0$, there exists $n_0 \in N$ such that $M(x_n, x_0, t) > 1-\varepsilon$ for all $n \geq n_0$.

(ii) a sequence $\{x_n\}$ in X is said to be Cauchy if for each ε > 0 and each t > 0, there exists $n_0 \in N$ such that $M(x_n, x_m, t) > 1 - \varepsilon$ for all n, m ≥ n_0.

(iii) A fuzzy metric space in which every Cauchy sequence is convergent is said to be complete.

Definition 2.4[21]. The self mappings A and S of a fuzzy metric space (X, M, ∗) are said to be compatible iff $\lim_{n\to\infty} M(ASx_n, SAx_n, t) = 1$ whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n = x$ for some x in X and t > 0.

Definition 2.5[4]. The self mappings A and S of a fuzzy metric space (X, M, ∗) are said to be compatible of type (A) if $\lim_{n\to\infty} d(ASx_n, SSx_n, t) = 1$ and $\lim_{n\to\infty} d(SAx_n, AAx_n, t) = 1$ whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n = x$ for some x in X and t > 0.

Definition 2.6[6] The self mappings A and S of a fuzzy metric space (X, M, ∗) are said to be compatible of type (P) if $\lim_{n\to\infty} d(SSx_n, AAx_n, t) = 1$ whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n = x$ for some x in X and t > 0.

Definition 2.7 [14] The self mappings A and S of a fuzzy metric space (X, M, ∗) are called reciprocally continuous on X if $\lim_{n\to\infty} ASx_n = Ax$ and $\lim_{n\to\infty} SAx_n = Sx$ whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n = x$ for some x in X.

Definition 2.8[16] The self mappings A and S of a fuzzy metric space (X, M, ∗) are called pointwise R-weakly commuting if there exists R > 0 such that M(ASx, SAx, t) ≥ M(Ax, Sx, t/R) for all x in X and t > 0. **Definition 2.9. [12]** The self mappings A and S of a metric space (X, d) are said to be compatible of type (E), if $\lim_{n\to\infty} AAx_n = \lim_{n\to\infty} ASx_n = S(t)$, whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = t$ and $\lim_{n\to\infty} Sx_n = t$, for some t ∈ X.

Definition 2.10 [7]. The self mappings A and S of a fuzzy metric space (X, M, ∗) are said to be compatible of type (E) iff $\lim_{n\to\infty} M(AAx_n, ASx_n, t) = 1$, $\lim_{n\to\infty} M(AAx_n, Sx_n, t) = 1$ $\lim_{n\to\infty} M(ASx_n, Sx_n, t) = 1$ and $\lim_{n\to\infty} M(SSx_n, SAx_n, t) = 1$, $\lim_{n\to\infty} M(SSx_n, Ax_n, t) = 1$ $\lim_{n\to\infty} M(Sx_n, Ax_n, t) = 1$ whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n = x$ for some x in X and t > 0.

The following examples show that the compatible of type (E) is independent with compatible, weekly compatible, compatible of type (A), compatible of type (P) and reciprocal continuous in fuzzy metric space.

Example 2.2 [7]. Let X = [0, 2] with the usual metric d(x, y) = |x − y|, define $M(x, y, t) = \frac{t}{t+d(x,y)}$ for all x, y ∈ X, t > 0 and a∗b = ab for all a,b ∈ [0, 1] then (X, M, ∗) is a fuzzy metric space.

We define self-mappings A and S as Ax =2, Sx = 0 for x ∈[0, 1] − { 1/2}, Ax = 0, Sx =2 for x = 1/2 and Ax = (2−x)/2,Sx = x/2 for x ∈(1, 2].
Then, A and S are not continuous at x = 1, 1/2.
Consider a sequence $\{x_n\}$ in X such that $x_n = 1 + 1/n$ for all n∈ N. Then,
we have $Ax_n = (2-x_n)/2 \rightarrow 1/2 = x$ and $Sx_n = x_n/2 \rightarrow 1/2 = x$.
Also, we have $AAx_n = A((2-x_n)/2) = 2\rightarrow 2$, $ASx_n = A(x_n/2) = 2\rightarrow 2$, S(x) = 2 and SSx_n =S(xn/2) = 0 → 0, $SAx_n = S((2-x_n)/2) = 0 \rightarrow 0$, A(x) = 0.
Therefore, {A, S} is compatible of type (E) but the pair {A, S} is neither compatible nor (compatible of type (A), compatible of type (P), reciprocal continuous).

Example 2.3 [7]. Let X = [0, 2] with the usual metric d(x, y) = |x − y|, define M(x, y, t) $=\frac{t}{t+d(x,y)}$ for all x, y ∈ X, t > 0 and a∗b = ab for all a,b ∈ [0, 1] then (X, M, ∗) is a fuzzy metric space. We define self-mappings A and S as Ax = Sx = 1 for x ∈ [0, 1), Ax = Sx = 4/3 for x = 1 and Ax = 2− x, Sx = x for x ∈(1, 2]. Consider a sequence $\{x_n\}$ in X such that $x_n = 1 + 1/n$ for all n∈ N. Then,
we have Ax_n = (2− xn) → 1 = x, and $Sx_n = x_n\rightarrow 1 = x$. Since, $2-x_n< 1$ for all n∈ N, we have $AAx_n = A (2-x_n) = 1 \rightarrow 1$, $ASx_n = A (x_n) = 2-x_n\rightarrow 1$ and $SSx_n = S(x_n) = x_n\rightarrow 1$, $SAx_n = S(2- x_n) = 1 \rightarrow 1$. Also, we have A(x) = 4/3 = S(t) but AS(x) = AS(1) = A(4/3) = 2/3, SA(x) = SA(1) = S(4/3) = 4/3. However, AS(x) ≠ SA(x) at x = 1. Therefore, {A, S} are not compatible of type (E) but it is compatible, compatible of type (A) and compatible of type (P).

Lemma 2.4[18] In a fuzzy metric space (X, M, ∗), if a ∗ a ≥ a for all a ∈ [0, 1] then a ∗ b = min {a, b} for all a, b ∈ [0, 1].

Lemma2. 5 [20] Let (X, M, ∗) be a fuzzy metric space with the condition: (FM6) $\lim_{n\to\infty} M(x, y, t) = 1$ for all x, y ∈ X. If there exists k ∈ (0, 1) such that M(x, y, kt) ≥ M(x, y, t) then x = y.

Lemma 2.6 [21] Let $\{y_n\}$ be a sequence in a fuzzy metric space (X, M, ∗) with the condition (FM6). If there exists k ∈ (0, 1) such that $M(y_n, y_{n+1}, kt) \geq M(y_{n-1}, y_n, t)$ for all t > 0 and n ∈ N, then $\{y_n\}$ is a Cauchy sequence in X.
We need the following proposition for the proof of our main result.

Proposition 2.7 [7].If A and S be compatible mappings of type (E) on a fuzzy metric space (X, M, ∗) and if one of function is continuous.Then, we have

(a) A(x) = S(x) and $\lim_{n\to\infty} AAx_n = \lim_{n\to\infty} SSx_n = \lim_{n\to\infty} ASx_n = \lim_{n\to\infty} SAx_n$,

(b) If these exist u ∈ X such that Au = Su = x then ASu = SAu.

whenever $\{x_n\}$ is a sequence in X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n =$ x for some x in X.

Proof: Let $\{x_n\}$ be a sequence of X such that $\lim_{n\to\infty} Ax_n = \lim_{n\to\infty} Sx_n =$ x for some x in X. Then by definition of compatible of type (E), we have $\lim_{n\to\infty} AAx_n =$ ASx_n = S(x). If A is a continuous mapping, then we get $\lim_{n\to\infty} AAx_n =$ A ($\lim_{n\to\infty} Ax_n$) = A(x). This implies A(x) = S(x). Also $\lim_{n\to\infty} AAx_n = \lim_{n\to\infty} SSx_n = \lim_{n\to\infty} ASx_n = \lim_{n\to\infty} SAx_n$. Similarly, if S is continuous then, we get the same result. This is the proof of part (a).
Again, suppose Au = Su = x for some u ∈ X. Then, ASu = A(Su) = At and
SAu = S(Au) = St. From (a), we have At = St. Hence, ASu = SAu.
This is the proof of part (b).

3. Main Results

If P, Q, S,T, A and B are self mappings in fuzzy metric space (X, M, ∗), we denote
M_α (x, y, t) = M(STx, Px, t) ∗M(ABy,Qy, t) ∗M(STx, ABy, t)∗M(ABy, Px, αt) ∗M(STx, Qy, (2 − α)t), for all x, y ∈ X, α ∈ (0, 2) and t > 0.

Theorem 3.1 Let (X, M, ∗) be a complete fuzzy metric space with a ∗ a ≥ a for all a ∈ [0, 1] and with the condition (FM 6). Let one of the mapping of self mappings (P, ST) and (Q, AB) of X be continuous such that

(i) P(X) ⊂ AB(X), Q(X) ⊂ ST(X);

(ii) there exists k ∈ (0, 1) such that M(Px, Qy, kt) ≥ M_α (x, y, t) for all x, y ∈ X, α ∈ (0, 2) and t > 0.

If (P, ST) and (Q, AB) compatible of type of (E) then P, Q, ST and AB have a unique common fixed point.
If the pair (A,B),(S,T),(Q,B) and (T,P) are Commuting mappings then A,B,S,T,P and Q have a unique
Common fixed point.

Proof. Let x_0 be any point in X. From condition (i), there exists x_1, x_2 ∈ X such that $Px_0 = ABx_1 = y_0$ and $Qx_1 = STx_2 = y_1$. Inductively, we can construct sequences $\{x_n\}$ and $\{y_n\}$ in X such that $Px_{2n} = ABx_{2n+1} = y_{2n}$ and $Qx_{2n+1} = STx_{2n+2} = y_{2n+1}$ for n = 0, 1, 2,.... for t > 0 and α = 1 − q with q ∈ (0, 1) in (ii), then, we have
M (Px_{2n}, Qx_{2n+1}, kt) ≥ M (STx_{2n}, Px_{2n}, t) ∗M (ABx_{2n+1}, Qx_{2n+1}, t) ∗M (STx_{2n}, ABx_{2n+1}, t) ∗
M (ABx_{2n+1}, Px_{2n}, (1 − q) t) ∗M (STx_{2n}, Qx_{2n+1}, (1 + q) t),
i.e., M (y_{2n}, y_{2n+1}, kt) ≥ M (y_{2n-1}, y_{2n}, t) ∗M (y_{2n}, y_{2n+1}, t) ∗M (y_{2n-1}, y_{2n}, t)* M (y_{2n}, y_{2n}, (1-q) t) ∗
M (y_{2n-1}, y_{2n+1}, (1 + q) t)
≥ M (y_{2n-1}, y_{2n}, t) ∗M (y_{2n}, y_{2n+1}, t) ∗M (y_{2n-1}, y_{2n}, t) ∗M (y_{2n}, y_{2n+1}, qt)
≥ M (y_{2n-1}, y_{2n}, t) ∗M (y_{2n}, y_{2n+1}, t) ∗M (y_{2n}, y_{2n+1}, qt).

Since t-norm ∗ is continuous, letting q → 1, we have
M (y_{2n}, y_{2n+1}, kt) ≥ M (y_{2n-1}, y_{2n}, t) ∗M (y_{2n}, y_{2n+1}, t) ∗M (y_{2n}, y_{2n+1}, t)
≥ M (y_{2n-1}, y_{2n}, t) ∗ M (y_{2n}, y_{2n+1}, t).

It follows that $M(y_{2n}, y_{2n+1}, kt) \geq M(y_{2n-1}, y_{2n}, t) * M(y_{2n}, y_{2n+1}, t)$.
Similarly, $M(y_{2n+1}, y_{2n+2}, kt) \geq M(y_{2n}, y_{2n+1}, t) * M(y_{2n+1}, y_{2n+2}, t)$.
Therefore, for all n even or odd, we have
$M(y_n, y_{n+1}, kt) \geq M(y_{n-1}, y_n, t) * M(y_n, y_{n+1}, t)$.
Consequently, $M(y_n, y_{n+1}, t) \geq M(y_{n-1}, y_n, k^{-1} t) * M(y_n, y_{n+1}, k^{-1} t)$ and hence
$M(y_n, y_{n+1}, t) \geq M(y_{n-1}, y_n, t) * M(y_n, y_{n+1}, k^{-1} t)$.
Since $M(y_n, y_{n+1}, k^{-m} t) \to 1$ as $k \to 0$, it follows that $M(y_n, y_{n+1}, kt) \geq M(y_{n-1}, y_n, t)$ for all $n \in N$ and $t > 0$. Therefore, by Lemma 2.6, $\{y_n\}$ is a Cauchy sequence. Since X is complete, then there exists a point z in X such that $y_n \to z$ as $n \to \infty$. Moreover, we have $y_{2n} = Px_{2n} = ABx_{2n+1} \to z$ and $y_{2n+1} = Qx_{2n+1} = STx_{2n+2} \to z$.
If P and ST are compatible of type (E) and one of mapping of the pair (P, ST) is continuous then by Proposition 2.7 we have Pz = STz. Since $P(X) \subset AB(X)$, there exists a point w in X such that Pz = ABw. Using condition (ii), with $\alpha = 1$, we have
$M(Pz, Qw, kt) \geq M(STz, Pz, t) * M(ABw, Qw, t) * M(STz, ABw, t) * M(ABw, Pz, t) * M(STz, Qw, t)$
$= M(Pz, Pz, t) * M(Pz, Qw, t) * M(Pz, Pz, t) * M(Pz, Pz, t) * M(Pz, Qw, t)$
$\geq M(Pz, Qw, t)$.

This implies Pz = Qw. Thus, we have Pz = STz = Qw = ABw.Also, we get
$M(Pz, Qx_{2n+1}, kt) \geq M(STz, Pz, t) * M(ABx_{2n+1}, Qx_{2n+1}, t) * M(STz, ABx_{2n+1}, t) * M(ABx_{2n+1}, Pz, t)$
$* M(STz, Qx_{2n+1}, t)$.

Letting $n \to \infty$, we get
$M(Pz, z, kt) \geq M(Pz, Pz, t) * M(Pz, z, t) * M(Pz, Pz, t) * M(Pz, Pz, t) * M(Pz, z, t)$
$\geq M(Pz, z, t)$.
Hence, we get STz = Pz =z. Therefore, z is common fixed point of P and ST.

Again, if Q and AB are compatible of type (E) and one of mappings of (Q, AB) is continuous, so we get Qw =ABw = Pz = z. By using proposition 2.7, we get QQw = QABw = ABQw = ABABw. Thus, we get Qz = ABz.

Also, using condition (ii) with $\alpha = 1$.We have,
$M(Px_{2n}, Qz, kt) \geq M(STx_{2n}, Px_{2n}, t) * M(ABz, Qz, t) * M(STx_{2n}, ABz, t) * M(ABz, Px_{2n}, t) * M(STx_{2n}, Qz, t)$.
Letting $n \to \infty$, we get
$M(z, Qz, kt) \geq M(z, z, t) * M(ABz, Qz, t) * M(z, ABz, t) * M(ABz, z, t) * M(z, Qz, t)$
$\geq M(z, Qz, t)$.

Hence, we have Qz = ABz =z. Therefore z is common fixed point of Q and AB.
Hence z is common fixed point of P, Q, ST and AB.
For uniqueness, suppose that Pw ($\neq$Pz = z) is another common fixed point of P, Q, ST and AB. Then, using condition (ii) with $\alpha = 1$, we have
$M(PPz, QPw, kt) = M(Pz, Pw, kt)$

$\geq$ M (STPz, PPz, t) $*$M (ABPw, QPw, t) $*$M (STPz, ABPw, t)$*$M(ABPw, PPz, t) $*$M(STPz, QPw, t)
= M (Pz, Pz, t) $*$M(Pw, Pw, t) $*$M(Pz, Pw, t) $*$M(Pw, Pz, t) $*$M(Pz, Pw, t)
$\geq$ M (Pz, Pw, t).
That is, Pw = Pz = z. Thus, z is a unique common fixed point of P, Q, ST and AB by using the commutativity of the pairs (A, B), (S, T),(Q,B) and (T,P) we can easily prove that z is a unique common fixed point of A,B,S,T,Pand Q. If we take T = B = Ix, an identity mapping of X in Theorem 3.2, we get the following result.

Corollary 3.3. Let (X, M, $*$) be a complete fuzzy metric space with a $*$ a $\geq$ a for all a $\in$ [0, 1] and with the condition (FM6). If one of the mapping of self mappings (P, Q) and (Q, A) of X is continuous such that for k $\in$ (0, 1) we have M (Px, Qy, kt) $\geq$ M_α(x, y, t) for all x, y $\in$ X, $\alpha \in$ (0, 2) and t > 0, and if (P, S) and (Q,A) are compatible of type of (E)
M_α(x,y,t) = M(Sx,Px,t)*M(Ay,Qy,t)*M(Sx,Ay,t)*M(Ay,Px,αt)*M(Sx,Qy,(2-α)t)
for all x,yϵ X,$\alpha\epsilon$ (0,2) and t>0

Similarly if we get the result for three self maps by taking S=A, T=B=I_x in the Theorem 3.2 and also by taking P=Q, T=B=I_x in theorem 3.2 and obtain for two self maps by taking P=Q, A=S, B=T=I_x in Theorem 3.2 then P, A, S, Q have a unique common fixed point.

Example 3.4. Let X = [2, 10] with the metric d defined by d(x, y) = |x − y| and define M(x, y, t) = $\frac{t}{t+d(x,y)}$ for all x, y $\in$ X, t > 0. Clearly (X, M, $*$) is a complete fuzzy metric space. Define P, Q, S, T, A and B: X→ X as follows;
Px = 2 for all x,
Qx = 2 if x < 4 and $\geq$ 5 Qx = 3+x if 4$\leq$ x < 5
Sx = if x $\leq$ 8, Sx = 8 if x > 8;
Ax = 2 if x < 4 or $\geq$ 5, Ax = 5 +x if 4 $\leq$ x < 5
Bx=Tx=x $\forall$ xϵ[2,10]

Then P, Q, S, T, A and B satisfy all the conditions of the above theorem and have a unique common fixed point x = 2.

Remark 3.5: The main theorem remains true if (P, ST) and (Q, AB) are pointwise R-weakly commuting pairs and one of the mappings (P, Q) or (ST, AB) is continuous and true for compatible, compatible of type (A) and compatible of type (P) in place of compatible of type (E) if P, ST, Q and AB are assumed to be continuous. Also, our result extend and generalize the results of Pant and Jha[17], Singh and Singh [11,12] and S. Kutukcu et al.[19] and improves other similar results in literature.

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