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Stability of Picard Iteration Procedure for Set-Valued Mapping in Intuitionistic Fuzzy Metric Space Using Various Contraction Conditions

Research Article

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Abstract: A lot of work has been done in intuitionistic fuzzy metric space. In this paper we discuss the stability of Picard iteration procedure for set-valued mapping using certain contraction conditions in intuitionistic fuzzy metric space.

Keywords: Stability, Picard iteration procedure, fixed point, set-valued mapping, intuitionistic fuzzy metric space.

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1. Introduction and Preliminaries

In 1965 Zadeh [32] introduced the concept of fuzzy set. Over the last three decades, many authors [1, 2, 4, 6, 14, 17, 20, 26–30] worked on this topic and developed the theory of fuzzy sets. In 1975 Kramosil and Michalek [15] introduced the concept of fuzzy metric space using continuous t-norms. Later on George and Veeramani [9] modified the concept of fuzzy metric space and developed few concepts of mathematical analysis. They also defined a Hausdorff topology on modified fuzzy metric space. In the paper [9], the concepts of fixed point theorem have been studied in fuzzy metric space. Several authors contributed in this field. Some of them are [8, 11, 12, 16, 18, 19, 22, 23, 31, 33]. The concept of intuitionistic fuzzy sets was first studied by Atanassor [3]. Park [21] introduced the generalization of intuitionistic fuzzy metric space which is known as modified intuitionistic fuzzy metric space. Let $\{x_n\}$ be a sequence in an intuitionistic fuzzy metric space $(X, M, N, *, \diamondsuit)$ and there exists a natural number n_0 for every $\epsilon > 0$ and $t > 0$ such that $M(x_n, x_m, t) > 1 - \epsilon$ and $N(x_n, x_m, t) < \epsilon$ for all $n, m \geq n_0$. Then this sequence is called Cauchy sequence. However, if every Cauchy sequence is convergent then the space $(X, M, N, *, \diamondsuit)$ is called complete.

Definition 1.1 ([25]). *A binary operation $* : [0,1] \times [0,1] \to [0,1]$ is called continuous t-norm if the following conditions are satisfied by $*$.*

(1) $*$ is commutative and associative,

(2) $*$ is continuous,

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(3) $a * 1 = a$ *for all* $a \in [0, 1]$

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

Definition 1.2 ([25]). *A binary operation* $\diamondsuit : [0, 1] \times [0, 1] \to [0, 1]$ *is called continuous t-conorm if the following conditions are satisfied by* $\diamondsuit$

(1) $\diamondsuit$ *is commutative and associative,*

(2) $\diamondsuit$ *is continuous,*

(3) $a\diamondsuit 0 = a$ *for all* $a \in [0, 1]$,

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

Definition 1.3 ([9, 10]). *Let* X *be a nonempty set and* $*$ *be a continuous t-norm. A fuzzy Set* M *on* $X \times X \times (0, +\infty)$ *is said to be a fuzzy metric on* X *if for any* $x, y, z \in X$ *and* $s, t > 0$, *the following conditions hold:*

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

(ii) $x = y$ *if and only if* $M(x, y, t) = 1$ *for all* $t > 0$;

(iii) $M(x, y, t) = M(y, x, t)$;

(iv) $M(x, z, t + s) \geq M(x, y, t) * M(y, z, s)$ *for all* $t, s > 0$*;*

(v) $M(x, y, \cdot) : (0, +\infty) \to (0, 1]$ *is continuous.*

The triplet $(X, M, *)$ is called a fuzzy metric space. Each fuzzy metric M on X generates Hausdorff topology τ_M on X whose base is the family of open M-balls $\{B_M(x, \varepsilon, t) : x \in X, \varepsilon \in (0, 1), t > 0\}$, where $B_M(x, \varepsilon, t) = \{y \in X \ : M(x, y, t) > 1 - \varepsilon\}$. Note that a sequence $\{x_n\}$ converges to $x \in X$ (with respect to τ_M) if and only if $\lim_{n\to\infty} M(x_n, xt) = 1$ for all $t > 0$.

Definition 1.4 ([21]). *Let* $*$ *be a continuous t-norm,* $\diamondsuit$ *be a continuous t-conorm and* X *be any non-empty set. An intuitionistic fuzzy metric on* X *is of the form*

$$F = \{((x, y, t), M(x, y, t), N(x, y, t)) : (x, y, t) \in X^2 \times [0, \infty]\}$$

where M *and* N *are fuzzy sets on* $X^2 \times [0, \infty]$, M *denotes the degree of nearness and* N *denotes the degree of non-nearness of* x *and* y *relative to* t *satisfying the following conditions: for all* $x, y, z \in X$*;* $s, t > 0$

(1) $M(x, y, t) + N(x, y, t) \leq 1 \ \forall \ (x, y, t) \in X^2 \times [0, \infty]$

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

(3) $M(x, y, t) = 1$ *if and only if* $x = y$;

(4) $M(x, y, t) = M(y, x, t)$;

(5) $M(x, y, s) * M(y, z, t) le M(x, z, s + t)$;

(6) $M(x, y, .) : (0, \infty) to (0, 1]$ *is continuous;*

(7) $N(x, y, t) > 0$;

(8) $N(x, y, t) = 0$ *if and only if* $x = y$;

(9) $N(x, y, t) = N(y, x, t)$;

(10) $N(x, y, s)\Diamond M(y, z, t) \geq N(x, z, s + t)$;

(11) $N(x, y, \cdot) : (0, \infty)$ *to* $(0, 1]$ *is continuous;*

If F *is a IFM on* X*, the pair* $(X,\ F)$ *will be called a intuitionistic fuzzy metric space or IFMS.*

Definition 1.5 ([24]). *Let K(X) denotes the set of all nonempty compact subsets of* X *and* $T : X \to K(X)$ *is a multi-valued mapping and* M *is a continuous function on* $X \times X \times (0, +\infty)$. *The Hausdorff fuzzy metric induced by a fuzzy metric is defined as follows: For* $x \in X$ and $A, B \in K(X)$ *we have,*

$$H_M(A, B, t) = \min\left\{\inf_{a\in A} M(a, B, t), \inf_{b\in B} M(A, b, t)\right\}$$

For all $t > 0$*, where* $M(x, A, t) = \sup_{a\in A} M(x, a, t)$ *then the triplet* $(K(X), H_M, *)$ *is called Hausdorff fuzzy metric space where* H_M *is the Hausdorff fuzzy metric induced by the fuzzy metric M.*

Definition 1.6 ([7]). *Let* $(X, M, N, *, \Diamond)$ *be an intuitionistic fuzzy metric space, then the triangular inequality is given by*

$$\frac{1}{M(x, y, t)} - 1 \leq \frac{1}{M(x, z, t)} - 1 + \frac{1}{M(z, y, t)} - 1$$

and $N(x, y, t) \leq N(x, z, t) + N(z, y, t)$ *for all* $x, y, z \in X$ *and* $t > 0$.

Definition 1.7 ([13, 20]). *Let* $T : X \to K(X)$ *be a mapping on an intuitionistic fuzzy metric space* $(X, M, N, *, \Diamond)$ *with a fixed point* p. *For* $x_0 \in X$*, consider the iteration procedure* $x_{n+1} \in f(T, x_n)$ *which converges to* p. *Let* $\{y_n\}$ *be any arbitrary sequence in* X. *If*

$$[(M(y_{n+1}, Ty_n, t) \to 1) \wedge (N(y_{n+1}, Ty_n, t) \to 0] \Rightarrow y_n \to p.$$

Then we say that the Picard iteration is T-stable.

Lemma 1.8 ([5]). *Let us consider* $\delta \in [0, 1)$ *to be a real number and* $\{\epsilon_n\}$ *be a sequence of positive numbers such that* $\lim_{n\to\infty} \epsilon_n = 0$. *If* $\{u_n\}$ *a sequence of positive real numbers such that* $u_{n+1} \leq \delta u_n + \epsilon_n$*, then* $\lim_{n\to\infty} u_n = 0$.

2. Main Result

Theorem 2.1. *Let* $(X, M, N, *, \Diamond)$ *be a complete intuitionistic fuzzy metric space such that* $\alpha, \beta \in [0, 1)$, $(\alpha + \beta) < 1$ *and* $T : X \to K(X)$ *is a multi-valued mapping which satisfies the contraction condition*

$$\frac{1}{H_M(Tx, Ty, t)} - 1 \leq \alpha \max\left\{\frac{1}{M(x, Ty, t)} - 1, \frac{1}{M(y, Ty, t)} - 1\right\} + \beta\left(\frac{1}{M(x, y, t)} - 1\right)$$

For all $x, y \in X$. *Suppose* p *is a fixed point of* T. *Let* $x_0 \in X$ *and* $x_{n+1} \in Tx_n$, $n = 0, 1, 2 \ldots$. *Suppose that* $\{y_n\}_{n=1}^{\infty}$ *be a sequence in* X *and set* $\epsilon_n = \left(\frac{1}{H_M(y_{n+1}, Ty_n, t)} - 1\right)$ *then the Picard iteration is T-Stable.*

Proof. Let $\lim_{n\to\infty} \epsilon_n = 0$, Now, using the triangular inequality, we get,

$$\begin{aligned}
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{M(Ty_n,p,t)} - 1 \\
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{H_M(Ty_n,Tp,t)} - 1 \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\ max\left\{\frac{1}{M(y_n,p,t)} - 1, \frac{1}{M(p,p,t)} - 1\right\} + \beta\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) + \beta\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + (\alpha+\beta)\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \qquad (1)
\end{aligned}$$

We can express (1) in the form $u_{n+1} \leq \delta u_n + \epsilon_n$, where

$$\begin{aligned}
0 \leq \delta &= (\alpha+\beta) < 1, \\
u_n &= \left(\frac{1}{M\left(y_n,p,t\right)} - 1\right), \\
\epsilon_n &= \left(\frac{1}{H_M\left(y_{n+1},Ty_n,t\right)} - 1\right)
\end{aligned}$$

If $n \to \infty$, then using Lemma 1.8, we get the required result $\lim_{n\to\infty} y_n = p$. □

Theorem 2.2. *Let $(X, M, N, *, \Diamond)$ be a complete intuitionistic fuzzy metric space such that $\alpha, \beta \in [0, 1)$, $(\alpha + \beta) < 1$ and $T : X \to K(X)$ is a multi-valued mapping which satisfies the contraction condition*

$$\frac{1}{H_M(Tx,Ty,t)} - 1 \leq \alpha\left\{\frac{\frac{1}{M(x,Ty,t)} - 1 - \frac{1}{M(y,Ty,t)} - 1}{\frac{1}{M(x,Ty,t)} - 1 + \frac{1}{M(y,Ty,t)} - 1}\right\}\left(\frac{1}{M\left(x,Ty,t\right)} - 1\right) + \beta\left(\frac{1}{M\left(x,y,t\right)} - 1\right).$$

For all $x, y \in X$. Suppose p is a fixed point of T. Let $x_0 \in X$ and $x_{n+1} \in Tx_n$, $n = 0, 1, 2\ldots$ Suppose that $\{y_n\}_{n=1}^{\infty}$ be a sequence in X and set $\epsilon_n = \left(\frac{1}{H_M\left(y_{n+1},Ty_n,t\right)} - 1\right)$ then the Picard iteration is T-Stable.

Proof. Let $\lim_{n\to\infty} \epsilon_n = 0$. Now, using the triangular inequality, we get,

$$\begin{aligned}
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{M(Ty_n,p,t)} - 1 \\
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{H_M(Ty_n,Tp,t)} - 1 \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left\{\frac{\frac{1}{M(y_n,Tp,t)} - 1 - \frac{1}{M(p,Tp,t)} - 1}{\frac{1}{M(y_n,Tp,t)} - 1 + \frac{1}{M(p,Tp,t)} - 1}\right\}\left(\frac{1}{M\left(y_n,Tp,t\right)} - 1\right) + \beta\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left\{\frac{\frac{1}{M(y_n,p,t)} - 1 - \frac{1}{M(p,p,t)} - 1}{\frac{1}{M(y_n,p,t)} - 1 + \frac{1}{M(p,p,t)} - 1}\right\}\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) + \beta\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) + \beta\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + (\alpha+\beta)\left(\frac{1}{M\left(y_n,p,t\right)} - 1\right) \qquad (2)
\end{aligned}$$

We can express (2) in the form $u_{n+1} \leq \delta u_n + \epsilon_n$, where

$$\begin{aligned}
0 \leq \delta &= (\alpha+\beta) < 1, \\
u_n &= \left(\frac{1}{M\left(y_n,p,t\right)} - 1\right), \\
\epsilon_n &= \left(\frac{1}{H_M\left(y_{n+1},Ty_n,t\right)} - 1\right)
\end{aligned}$$

If $n \to \infty$, then using Lemma 1.8, we get the required result $\lim_{n\to\infty} y_n = p$. □

Theorem 2.3. *Let $(X, M, N, *, \Diamond)$ be a complete intuitionistic fuzzy metric space such that $\alpha, \beta \in [0,1)$, $(\alpha+\beta) < 1$ and $T : X \to K(X)$ is a multi-valued mapping which satisfies the contraction condition*

$$\frac{1}{H_M(Tx,Ty,t)} - 1 \leq \alpha \left\{ \frac{\left(\frac{1}{M(x,Ty,t)} - 1\right)\left(\frac{1}{M(y,Tx,t)} - 1\right)\left(\frac{1}{M(y,Ty,t)} - 1\right)}{\left(\frac{1}{M(x,y,t)} - 1\right)} \right\} + \beta\left(\frac{1}{M(x,Ty,t)} - 1\right).$$

For all $x, y \in X$. Suppose p is a fixed point of T. Let $x_0 \in X$ and $x_{n+1} \in Tx_n$, $n = 0,1,2\ldots$ Suppose that $\{y_n\}_{n=1}^{\infty}$ be a sequence in X and set $\epsilon_n = \left(\frac{1}{H_M(y_{n+1},Ty_n,t)} - 1\right)$ then the Picard iteration is T-Stable.

Proof. Let $\lim_{n\to\infty} \epsilon_n = 0$. Now, using the triangular inequality, we get,

$$\begin{aligned}
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{M(Ty_n,p,t)} - 1 \\
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{H_M(Ty_n,Tp,t)} - 1 \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left\{ \frac{\left(\frac{1}{M(y_n,Tp,t)} - 1\right)\left(\frac{1}{M(p,Ty_n,t)} - 1\right)\left(\frac{1}{M(p,Tp,t)} - 1\right)}{\left(\frac{1}{M(y_n,p,t)} - 1\right)} \right\} + \beta\left(\frac{1}{M(y_n,Tp,t)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left\{ \frac{\left(\frac{1}{M(y_n,p,t)} - 1\right)\left(\frac{1}{M(p,Ty_n,t)} - 1\right)\left(\frac{1}{M(p,p,t)} - 1\right)}{\left(\frac{1}{M(y_n,p,t)} - 1\right)} \right\} + \beta\left(\frac{1}{M(y_n,p,t)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \beta\left(\frac{1}{M(y_n,p,t)} - 1\right) \qquad (3)
\end{aligned}$$

We can express (3) in the form $u_{n+1} \leq \delta u_n + \epsilon_n$, where

$$\begin{aligned}
0 \leq \delta &= \beta < 1, \\
u_n &= \left(\frac{1}{M(y_n,p,t)} - 1\right), \\
\epsilon_n &= \left(\frac{1}{H_M(y_{n+1},Ty_n,t)} - 1\right)
\end{aligned}$$

If $n \to \infty$, then using Lemma 1.8, we get the required result $\lim_{n\to\infty} y_n = p$. □

Theorem 2.4. *Let $(X, M, N, *, \Diamond)$ be a complete intuitionistic fuzzy metric space such that $\alpha, \beta, \gamma \in [0,1)$, $(\alpha+\beta) < 1$ and $T : X \to K(X)$ is a multi-valued mapping which satisfies the contraction condition*

$$\frac{1}{H_M(Tx,Ty,t)} - 1 \leq \alpha\left(\frac{1}{M(x,y,t)} - 1\right) + \beta\left(\frac{1}{M(x,Ty,t)} - 1\right) + \gamma\left(\frac{1}{M(y,Ty,t)} - 1\right).$$

For all $x, y \in X$. Suppose p is a fixed point of T. Let $x_0 \in X$ and $x_{n+1} \in Tx_n$, $n = 0,1,2\ldots.$ Suppose that $\{y_n\}_{n=1}^{\infty}$ be a sequence in X and set $\epsilon_n = \left(\frac{1}{H_M(y_{n+1},Ty_n,t)} - 1\right)$ then the Picard iteration is T-Stable.

Proof. Let $\lim_{n\to\infty} \epsilon_n = 0$. Now, using the triangular inequality, we get,

$$\begin{aligned}
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{M(Ty_n,p,t)} - 1 \\
\frac{1}{M(y_{n+1},p,t)} - 1 &\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \frac{1}{H_M(Ty_n,Tp,t)} - 1 \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left(\frac{1}{M(y_n,p,t)} - 1\right) + \beta\left(\frac{1}{M(y_n,Tp,t)} - 1\right) + \gamma\left(\frac{1}{M(p,Tp,t)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left(\frac{1}{M(y_n,p,t)} - 1\right) + \beta\left(\frac{1}{M(y_n,p,t)} - 1\right) + \gamma\left(\frac{1}{M(p,p,t)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + \alpha\left(\frac{1}{M(y_n,p,t)} - 1\right) + \beta\left(\frac{1}{M(y_n,p,t)} - 1\right) \\
&\leq \frac{1}{H_M(y_{n+1},Ty_n,t)} - 1 + (\alpha+\beta)\left(\frac{1}{M(y_n,p,t)} - 1\right) \qquad (4)
\end{aligned}$$

We can express (4) in the form $u_{n+1} \leq \delta u_n + \epsilon_n$, where

$$\begin{aligned} 0 \leq \delta &= (\alpha + \beta) < 1, \\ u_n &= \left(\frac{1}{M(y_n, p, t)} - 1 \right), \\ \epsilon_n &= \left(\frac{1}{H_M(y_{n+1}, Ty_n, t)} - 1 \right) \end{aligned}$$

If $n \to \infty$, then using Lemma 1.8, we get the required result $\lim_{n\to\infty} y_n = p$. □

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