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Some Common Fixed Point Results for Generalized Contraction in b-metric-like Spaces

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ABSTRACT: In this paper, some common fixed point results are established for mappings satisfying new contractive conditions in b-metric-like spaces. These results extend, generalize and improve many existing results in the literature. Also, some examples are given here to verify the applicability of obtained results.

Key Words: Common coupled fixed points, b-metric-like space, contractive maps.

Contents

1. Introduction

Theory of fixed points has played a very important role in the field of non linear analysis. It has been extensively used in various branches of engineering and sciences. It is well known that in 1922, Polish mathematician Stefan Banach [5] proved a fixed point theorem known as Banach Contraction Principle which has been widely used in Metrical fixed point theory till now. Then, the idea of b-metric space was introduced and used by Bourbaki [8] and Bakhtin [4] which generalized the Banach contraction principle in metric spaces. The idea was further modified by Czerwik [10] with an axiom which was weaker than the triangular inequality. After few years, M.A. Alghamdi [2] presented the concept of b-metric-like space by considering non-zero self distance property. Since then numerous papers dealt with fixed point theory for single valued and multivalued operators in b-metric and its generalized spaces([7], [11], [12], [13], [26]).

In [6], Bhaskar and Lakshmikantham put forward the concept of coupled fixed points for non linear contraction mappings. Later on, V. Lakshmikantham and L. Ćirić [25] generalized these results and proved coupled coincidence and common coupled fixed point theorems for nonlinear contractions in partially ordered metric spaces.The study of common coupled fixed points of non linear mappings with different contractive conditions has been at the centre of intensive research activity. For more details on the fixed point results and their applications in different metric spaces, one can refer to ([1], [3], [4], [9], [15], [16], [17], [18], [19], [20], [21], [22],[23], [24], [27]).

In this paper, some common coupled fixed point theorems satisfying new contractive conditions are investigated. Furthermore, some useful deductions are also presented to verify the effectiveness and applicability of results.

2. Preliminaries

Let us recall definitions and properties of some related metric spaces and mappings:

Definition 2.1 *[4] For a non empty set X, the function $B : X \times X \to [0, +\infty)$ is called a b-metric space on the set X if it satisfies the following properties:*

$(B1)$ $B(x, y) = 0 \Leftrightarrow x = y$;
$(B2)$ $B(x, y) = B(y, x)$;
$(B3)$ $B(x, y) \leq s(B(x, z) + B(z, y))$ *for all* $x, y, z \in X$ (*where* $s \geq 1$).

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The pair (X, B) is called a b-metric space.

Remark 2.1 *It is clear that definition of b-metric space is an extension of usual metric space.*

Example 2.1 *[4] The space $l_p (0 < p < 1)$ where*

$$l_p = \{(x_n) \subset \mathbb{R} : \sum_{n=1}^{\infty} |x_n|^p < \infty\},$$

together with function $B : l_p \times l_p \to \mathbb{R}$ defined as

$$B(x, y) = \left(\sum_{n=1}^{\infty} |x_n - y_n|^p \right)^{\frac{1}{p}}$$

where $x = x_n, \ y = y_n \in l_p$ is a b-metric space. By an elementary calculation, we obtain that

$$B(x, z) \leq 2^{\frac{1}{p}} [B(x, y) + B(y, z)].$$

Definition 2.2 *[2] For a non empty set X, the function $B_{ML} : X \times X \to [0, +\infty)$ is called a b-metric space on the set X if it satisfies the following properties:*

$$\begin{array}{ll} (B_{ML}1) & B_{ML}(x, y) = 0 \Rightarrow x = y; \\ (B_{ML}2) & B_{ML}(x, y) = B_{ML}(y, x); \\ (B_{ML}3) & B_{ML}(x, y) \leq s(B_{ML}(x, z) + B_{ML}(z, y)) \quad for \quad all \quad x, y, z \in X \quad (where \quad s \geq 1). \end{array}$$

The set X equipped with a metric B_{ML} defined on it, is called a b-metric like space and is denoted by (X, B_{ML}).

Example 2.2 *[2] Let $X = [0, \infty)$ and let the function $B_{ML} : X^2 \to [0, \infty)$ be defined by $B_{ML}(x, y) = (x+y)^2$. Then (X, B_{ML}) is a b-metric-like space with constant $s = 2$. It is clear that (X, B_{ML}) is neither a b-metric nor metric-like space as for all $x, y, z \in X$,*

$$\begin{aligned} B_{ML}(x, y) = (x + y)^2 &\leq (x + z + z + y)^2 \\ &= (x + z)^2 + (z + y)^2 + 2(x + z)(z + y) \\ &\leq 2[(x + z)^2 + (z + y)^2] \\ &= 2[B_{ML}(x, z) + B_{ML}(z, y)] \end{aligned}$$

and so $(B_{ML}3)$ holds. Clearly,$(B_{ML}1)$ and$(B_{ML}2)$ hold.

Definition 2.3 *[2] Let (X, B_{ML}) be a b-metric-like space. For any sequence $\{a_n\}$ of points of a non-empty set X, a point $a \in X$ is said to be the limit of the sequence $\{a_n\}$ if for each $\epsilon > 0$, there exists some $n_\epsilon \in \mathbb{N}$, for which $B_{ML}(a_n, a) < \epsilon$ for all $n \geq n_\epsilon$ and the sequence a_n is said to be converging to a. It can also be written as $lim_{n \to \infty} a_n = a$.*

Definition 2.4 *[2] For a b-metric-like space (X, B_{ML}),*
(i) A sequence a_n in X is called Cauchy if for each $\epsilon > 0$, there exists some $n_\epsilon \in \mathbb{N}$, for which $B_{ML}(a_n, a_m) < \epsilon$ for all $n, m \geq n_\epsilon$;
(ii) A b-metric-like space (X, B_{ML}) is called complete iff *every Cauchy sequence a_n in X converges in X.*

Definition 2.5 *[6] A point $(x, y) \in X \times X$ is called a coupled fixed point for $D : X \times X \to X$ if $D(x, y) = x$ and $D(y, x) = y$.*

Example 2.3 *[6] Let $X = [0, 1]$ and the mapping $D : X \times X \to X$ is defined by $D(x, y) = \frac{x+y}{2}$ for all $x, y \in X$. Then $(0, 0)$ and $(1, 1)$ are two coupled fixed points of D.*

Definition 2.6 *[25] A point $(x, y) \in X \times X$ is called a coupled coincidence point for $D_1, D_2 : X \times X \to X$ if $D_1(x, y) = D_2(x, y)$ and $D_1(y, x) = D_2(y, x)$.*

Example 2.4 *[25] Let $X = \mathbb{R}$ and the mappings $D_1, D_2 : X \times X \to X$ are defined as $D_1(x, y) = x + y - xy + sin(x + y)$ and $D_2(x, y) = x + y + cos(x + y)$ for all $x, y \in X$. Then $\left(0, \frac{\pi}{4}\right)$ and $\left(\frac{\pi}{4}, 0\right)$ are two coupled coincidence points of D_1 and D_2.*

Definition 2.7 *[25] A point $(x, y) \in X \times X$ is called a common coupled fixed point for $D_1, D_2 : X \times X \to X$ if $x = D_1(x, y) = D_2(x, y)$ and $y = D_1(y, x) = D_2(y, x)$.*

Example 2.5 *[25] Let $X = \mathbb{R}$ and the mappings $D_1, D_2 : X \times X \to X$ are defined as $D_1(x, y) = xy$ and $D_2(x, y) = x + (y - x)^2$ for all $x, y \in X$. Then $(0, 0)$ and $(1, 1)$ are two common coupled fixed points of D_1 and D_2.*

3. Results and Discussion

Theorem 3.1 *Let (X, B_{ML}) be a complete b-metric-like space having a parameter $K \geq 1$ and let the mappings $D_1, D_2 : X \times X \to X$ satisfy*

$$\begin{aligned} B_{ML}(D_1(a,b), D_2(u,v)) \quad \leq \quad & \alpha\frac{(B_{ML}(a,u) + B_{ML}(b,v))}{2} + \beta\frac{B_{ML}(a, D_1(a,b))B_{ML}(u, D_2(u,v))}{(1 + B_{ML}(a,u) + B_{ML}(b,v))} \\ & +\gamma\frac{B_{ML}(u, D_1(a,b))B_{ML}(a, D_2(u,v))}{(1 + B_{ML}(a,u) + B_{ML}(b,v))}; \end{aligned} \tag{3.1}$$

for all $a, b, u, v \in X$ and $\alpha, \beta \geq 0$ with $K\alpha + \beta < 1$ and $\alpha + \gamma < 1$. Then D_1 and D_2 have a unique common coupled fixed point in X.

Proof: Step 1: Firstly, it is shown that $\{a_n\}$, $\{b_n\}$ are Cauchy sequences in X.
Let $a_0, b_0 \in X$ be arbitrary points. Define $a_{2k+1} = D_1(a_{2k}, b_{2k})$, $b_{2k+1} = D_1(b_{2k}, a_{2k})$ and $a_{2k+2} = D_2(a_{2k+1}, b_{2k+1})$, $b_{2k+2} = D_2(b_{2k+1}, a_{2k+1})$ for $k = 0, 1, 2, ...$
Now,

$$\begin{aligned} B_{ML}(a_{2k+1}, a_{2k+2}) =& B_{ML}(D_1(a_{2k}, b_{2k}), D_2(a_{2k+1}, b_{2k+1})) \\ \leq& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1})}{2} \\ & + \beta\frac{B_{ML}(a_{2k}, D_1(a_{2k}, b_{2k}))B_{ML}(a_{2k+1}, D_2(a_{2k+1}b_{2k+1}))}{(1 + B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1}))} \\ & + \gamma\frac{B_{ML}(a_{2k+1}, D_1(a_{2k}, b_{2k}))B_{ML}(a_{2k}, D_2(a_{2k+1}, b_{2k+1}))}{(1 + B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1}))} \\ =& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1})}{2} + \beta\frac{B_{ML}(a_{2k}, a_{2k+1})B_{ML}(a_{2k+1}, a_{2k+2})}{(1 + B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1}))} \\ & + \gamma\frac{B_{ML}(a_{2k+1}, a_{2k+1})B_{ML}(a_{2k}, a_{2k+2})}{(1 + B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1}))} \\ \leq& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1})}{2} + \beta\frac{B_{ML}(a_{2k}, a_{2k+1})B_{ML}(a_{2k+1}, a_{2k+2})}{(1 + B_{ML}(a_{2k}, a_{2k+1}) + B_{ML}(b_{2k}, b_{2k+1}))} \\ & + \gamma[2B_{ML}(a_{2k+1}, a_{2k+2})] \\ \leq& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1})}{2} + \alpha\frac{B_{ML}(b_{2k}, b_{2k+1})}{2} + \beta B_{ML}(a_{2k+1}, a_{2k+2}) + \gamma[2B_{ML}(a_{2k+1}, a_{2k+2})] \\ \Rightarrow (1 - \beta - 2\gamma)B_{ML}(a_{2k+1}, a_{2k+2}) \leq& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1})}{2} + \alpha\frac{B_{ML}(b_{2k}, b_{2k+1})}{2} \\ B_{ML}(a_{2k+1}, a_{2k+2}) \leq& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1})}{2(1 - \beta - 2\gamma)} + \alpha\frac{B_{ML}(b_{2k}, b_{2k+1})}{2(1 - \beta - 2\gamma)} \\ \Rightarrow B_{ML}(a_{2k+1}, a_{2k+2}) \leq& \alpha\frac{B_{ML}(a_{2k}, a_{2k+1})}{2(1 - \beta)} + \alpha\frac{B_{ML}(b_{2k}, b_{2k+1})}{2(1 - \beta)}. \end{aligned}$$

Continuing in the same manner, we have

$$B_{ML}(b_{2k+1}, b_{2k+2}) \leq \alpha\frac{B_{ML}(b_{2k}, b_{2k+1})}{2(1 - \beta)} + \alpha\frac{B_{ML}(a_{2k}, a_{2k+1})}{2(1 - \beta)}. \tag{3.2}$$

Adding (3) and (3.2), we get

$$\begin{aligned}[B_{ML}(a_{2k+1},a_{2k+2})+B_{ML}(b_{2k+1},b_{2k+2})] &\leq \frac{\alpha}{1-\beta}[B_{ML}(a_{2k},a_{2k+1})+B_{ML}(b_{2k},b_{2k+1})]\\ &= h\ [B_{ML}(a_{2k},a_{2k+1})+B_{ML}(b_{2k},b_{2k+1})];\end{aligned}$$

where $0<h=\frac{\alpha}{1-\beta}<1$.
Similarly,

$$B_{ML}(a_{2k+2},a_{2k+3})\leq \alpha\frac{B_{ML}(a_{2k+1},a_{2k+2})}{2(1-\beta)}+\alpha\frac{B_{ML}(b_{2k+1},b_{2k+2})}{2(1-\beta)}; \tag{3.3}$$

and

$$B_{ML}(b_{2k+2},b_{2k+3})\leq \alpha\frac{B_{ML}(b_{2k+1},b_{2k+2})}{2(1-\beta)}+\alpha\frac{B_{ML}(a_{2k+1},a_{2k+2})}{2(1-\beta)}. \tag{3.4}$$

Adding inequalities (3.3) and (3.4), we have

$$\begin{aligned}[B_{ML}(a_{2k+2},a_{2k+3})+B_{ML}(b_{2k+2},b_{2k+3})] &\leq \frac{\alpha}{1-\beta}[B_{ML}(a_{2k+1},a_{2k+2})+B_{ML}(b_{2k+1},b_{2k+2})]\\ &= h\ [B_{ML}(a_{2k+1},a_{2k+2})+B_{ML}(b_{2k+1},b_{2k+2})].\end{aligned}$$

Continuing in this way,

$$[B_{ML}(a_n,a_{n+1})+B_{ML}(b_n,b_{n+1})]\leq h\ [B_{ML}(a_{n-1},a_n)+B_{ML}(b_{n-1},b_n)]\leq ...h^n\ [B_{ML}(a_0,a_1)+B_{ML}(b_0,b_1)].$$

Now, if we put $[B_{ML}(a_n,a_{n+1})+B_{ML}(b_n,b_{n+1})]=\delta_n$, then $\delta_n\leq h\ \delta_{n-1}\leq h^n\ \delta_0$. For $m>n$, we have

$$\begin{aligned}[B_{ML}(a_n,a_m)+B_{ML}(b_n,b_m)] \leq& K[B_{ML}(a_n,a_{n+1})+B_{ML}(b_n,b_{n+1})]+...+K^{m-n}[B_{ML}(a_{m-1},a_m)+B_{ML}(b_{m-1},b_m)]\\ \leq& K\ h^n\delta_0+K^2\ hn+1\delta_0+...+K^{m-n}\ h^{m-1}\delta_0\\ \leq& Kh^n[1+(Kh)+(Kh)^2+...]\delta_0\\ \leq& \frac{Kh^n}{1-Kh}\delta_0\ as\ n\to\infty.\end{aligned}$$

This shows that $\{a_n\}$ and $\{b_n\}$ are Cauchy sequences in X. Since X is a complete b-metric-like space, there exists $a,b\in X$ such that $a_n\to a$ and $b_n\to b$ as $n\to\infty$.

Step 2:Now, it is shown that (a,b) is common coupled fixed point of D_1 and D_2 *i.e.* $a=D_1(a,b)$ and $b=D_1(b,a)$.
Let us suppose on the contrary that $a\neq D_1(a,b)$ and $b\neq D_1(b,a)$ so that

$$B_{ML}(a,D_1(a,b))=l_1>0\ and\ B_{ML}(b,D_1(b,a))=l_2>0.$$

Consider

$$\begin{aligned}l_1 &= B_{ML}(a,D_1(a,b))\leq K[B_{ML}(a,a_{2k+2})+B_{ML}(a_{2K+2},D_1(a,b)]\\ &= KB_{ML}(a,a_{2k+2})+KB_{ML}(D_2(a_{2k+1},b_{2k+1}),D_1(a,b))\\ &\leq KB_{ML}(a,a_{2k+2})+K\alpha\frac{(B_{ML}(a_{2k+1},a)+B_{ML}(b_{2k+1},b))}{2}\\ &\quad +K\beta\frac{B_{ML}(a,D_1(a,b))B_{ML}(a_{2k+1},D_2(a_{2k+1},b_{2k+1}))}{1+B_{ML}(a_{2k+1,a}+B_{ML}(b_{2k+1},b))}+K\gamma\frac{B_{ML}(a_{2k+1},D_1(a,b))B_{ML}(a,a_{2k+2})}{1+B_{ML}(a_{2k+1},a)+B_{ML}(b_{2k+1},b)}.\end{aligned}$$

By taking $k\to\infty$, we get $l_1\leq 0$ which is a contradiction.
Therefore, $B_{ML}(a,D_1(a,b))=0$. This implies $a=D_1(a,b)$. Similarly, it can be proved that $b=D_1(b,a)$. In the same way, it can be easily shown that $a=D_2(a,b)$ and $b=D_2(b,a)$. Hence (a,b) is a common coupled fixed point of D_1 and D_2.

Step 3: Now it will be proved that D_1 and D_2 have a unique common coupled fixed point. Let $(a^*, b^*) \in X \times X$ be another common coupled fixed point of D_1 and D_2. Then,

$$\begin{aligned}
B_{ML}(a,a^*) &= B_{ML}(D_1(a,b), D_2(a^*,b^*)) \\
&\leq \alpha\frac{(B_{ML}(a,a^*)+B_{ML}(b,b^*))}{2} + \beta\frac{B_{ML}(a,D_1(a,b))B_{ML}(a^*,D_2(a^*,b^*))}{(1+B_{ML}(a,a^*)+B_{ML}(b,b^*))} \\
&\quad +\gamma\frac{B_{ML}(a^*,D_1(a,b))B_{ML}(a,D_2(a^*,b^*))}{(1+B_{ML}(a,a^*)+B_{ML}(b,b^*))} \\
&= \alpha\frac{(B_{ML}(a,a^*)+B_{ML}(b,b^*))}{2} + \frac{\beta B_{ML}(a,a)B_{ML}(a^*,a^*)}{(1+B_{ML}(a,a^*)+B_{ML}(b,b^*))} \\
&\quad +\gamma\frac{B_{ML}(a^*,a)B_{ML}(a,a^*)}{(1+B_{ML}(a,a^*)+B_{ML}(b,b^*))} \\
\Rightarrow B_{ML}(a,a*) &\leq \alpha\frac{B_{ML}(a,a^*)}{2} + \alpha\frac{B_{ML}(b,b^*)}{2} + 4\beta B_{ML}(a,a^*) + \gamma B_{ML}(a^*,a) \\
&\leq \frac{2}{(2-\alpha-8\beta-2\gamma)}B_{ML}(b,b^*) \\
&\leq \frac{2}{(2-\alpha-2\beta)}B_{ML}(b,b^*). \qquad (3.5)
\end{aligned}$$

Similarly, it can be proved that

$$B_{ML}(b,b^*) \leq \frac{2}{(2-\alpha-2\beta)}B_{ML}(a,a^*). \qquad (3.6)$$

Adding (3.5) and (3.6), we get

$$\begin{aligned}
B_{ML}(a,a^*)+B_{ML}(b,b^*) &\leq \frac{2}{(2-\alpha-2\beta)}[B_{ML}(a,a^*)+B_{ML}(b,b^*)] \\
(2-2\alpha-2\gamma)[B_{ML}(a,a^*)+B_{ML}(b,b^*)] &\leq 0 \\
\Rightarrow B_{ML}(a,a^*)+B_{ML}(b,b^*) &= 0.
\end{aligned}$$

This implies, $a = a^*$ and $b = b^*$. □

Corollary 3.1 *Let (X, B_{ML}) be a complete b-metric-like space having a parameter $K \geq 1$ and let the mapping $D_2 : X \times X \to X$ satisfy*

$$\begin{aligned}
B_{ML}(D_1(a,b), D_1(u,v)) \leq\ & \alpha\frac{(B_{ML}(a,u)+B_{ML}(b,v))}{2} + \beta\frac{(B_{ML}(a,D_1(a,b))B_{ML}(u,D_1(u,v)))}{(1+B_{ML}(a,u)+B_{ML}(b,v))} + \\
& \gamma\frac{(B_{ML}(u,D_1(a,b))B_{ML}(a,D_1(u,v)))}{(1+B_{ML}(a,u)+B_{ML}(b,v))};
\end{aligned}$$

for all $a, b, u, v \in X$ and $\alpha, \beta \geq 0$ with $K\alpha + \beta < 1$ and $\alpha + \gamma < 1$. Then D_1 has a unique coupled fixed point in X.

Proof: The above result can be easily proved by assuming $D_1 = D_2$ in Theorem 3.1. □

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