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Common fixed point of a power graphic contraction pair in partial metric spaces endowed with a graph

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Abstract
In this paper, we initiate a study of fixed point results in the setup of partial metric spaces endowed with a graph. The concept of a power graphic contraction pair of two mappings is introduced. Common fixed point results for such maps without appealing to any form of commutativity conditions defined on a partial metric space endowed with a directed graph are obtained. These results unify, generalize and complement various known comparable results from the current literature.
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1 Introduction and preliminaries

Consistent with Jachymski [1], let X be a nonempty set and d be a metric on X. A set $\{(x,x) : x \in X\}$ is called a diagonal of $X \times X$ and is denoted by Δ. Let G be a directed graph such that the set $V(G)$ of its vertices coincides with X and $E(G)$ is the set of the edges of the graph with $\Delta \subseteq E(G)$. Also assume that the graph G has no parallel edges. One can identify a graph G with the pair $(V(G), E(G))$. Throughout this paper, the letters $\mathbb{R}$, $\mathbb{R}^+$, ω and $\mathbb{N}$ will denote the set of real numbers, the set of nonnegative real numbers, the set of nonnegative integers and the set of positive integers, respectively.

Definition 1.1 [1] A mapping $f : X \to X$ is called a Banach G-contraction or simply G-contraction if

(a_1) for each $x, y \in X$ with $(x,y) \in E(G)$, we have $(f(x), f(y)) \in E(G)$,
(a_2) there exists $\alpha \in (0,1)$ such that for all $x, y \in X$ with $(x,y) \in E(G)$ implies that $d(f(x), f(y)) \le \alpha d(x,y)$.

Let $X^f := \{x \in X : (x, f(x)) \in E(G) \text{ or } (f(x), x) \in E(G)\}$.

Recall that if $f : X \to X$, then a set $\{x \in X : x = f(x)\}$ of all fixed points of f is denoted by $F(f)$. A self-mapping f on X is said to be

(1) a Picard operator if $F(f) = \{x^*\}$ and $f^n(x) \to x^*$ as $n \to \infty$ for all $x \in X$;
(2) a weakly Picard operator if $F(f) \neq \emptyset$ and for each $x \in X$, we have $f^n(x) \to x^* \in F(f)$ as $n \to \infty$;

(3) orbitally continuous if for all $x, a \in X$, we have

$$\lim_{k\to\infty} f^{n_k}(x) = a \quad \text{implies} \quad \lim_{i\to\infty} f\bigl(f^{n_k}(x)\bigr) = f(a).$$

The following definition is due to Chifu and Petrusel [2].

Definition 1.2 An operator $f : X \to X$ is called a Banach G-graphic contraction if

(b_1) for each $x, y \in X$ with $(x, y) \in E(G)$, we have $(f(x), f(y)) \in E(G)$,
(b_2) there exists $\alpha \in [0, 1)$ such that

$$d\bigl(f(x), f^2(x)\bigr) \leq \alpha d\bigl(x, f(x)\bigr) \quad \text{for all } x \in X^f.$$

If x and y are vertices of G, then a path in G from x to y of length $k \in \mathbb{N}$ is a finite sequence $\{x_n\}$, $n \in \{0, 1, 2, \ldots, k\}$ of vertices such that $x_0 = x$, $x_k = y$ and $(x_{i-1}, x_i) \in E(G)$ for $i \in \{1, 2, \ldots, k\}$.

Notice that a graph G is connected if there is a path between any two vertices and it is weakly connected if $\widetilde{G}$ is connected, where $\widetilde{G}$ denotes the undirected graph obtained from G by ignoring the direction of edges. Denote by G^{-1} the graph obtained from G by reversing the direction of edges. Thus,

$$E\bigl(G^{-1}\bigr) = \bigl\{(x, y) \in X \times X : (y, x) \in E(G)\bigr\}.$$

Since it is more convenient to treat $\widetilde{G}$ as a directed graph for which the set of its edges is symmetric, under this convention, we have that

$$E(\widetilde{G}) = E(G) \cup E\bigl(G^{-1}\bigr).$$

If G is such that $E(G)$ is symmetric, then for $x \in V(G)$, the symbol $[x]_G$ denotes the equivalence class of the relation R defined on $V(G)$ by the rule:

yRz if there is a path in G from y to z.

A graph G is said to satisfy the property (A) (see also [2]) if for any sequence $\{x_n\}$ in $V(G)$ with $x_n \to x$ as $n \to \infty$ and $(x_n, x_{n+1}) \in E(G)$ for $n \in \mathbb{N}$ implies that $(x_n, x) \in E(G)$.

Jachymski [1] obtained the following fixed point result for a mapping satisfying the Banach G-contraction condition in metric spaces endowed with a graph.

Theorem 1.3 [1] *Let (X, d) be a complete metric space and G be a directed graph and let the triple (X, d, G) have a property* (A). *Let $f : X \to X$ be a G-contraction. Then the following statements hold*:

1. *$F_f \neq \emptyset$ if and only if $X_f \neq \emptyset$*;
2. *if $X_f \neq \emptyset$ and G is weakly connected, then f is a Picard operator*;
3. *for any $x \in X_f$ we have that $f|_{[x]_{\widetilde{G}}}$ is a Picard operator*;
4. *if $f \subseteq E(G)$, then f is a weakly Picard operator.*

Gwodzdz-Lukawska and Jachymski [3] developed the Hutchinson-Barnsley theory for finite families of mappings on a metric space endowed with a directed graph. Bojor [4] obtained a fixed point of a φ-contraction in metric spaces endowed with a graph (see also [5]). For more results in this direction, we refer to [2, 6, 7].

On the other hand, Mathews [8] introduced the concept of a partial metric to obtain appropriate mathematical models in the theory of computation and, in particular, to give a modified version of the Banach contraction principle more suitable in this context. For examples, related definitions and work carried out in this direction, we refer to [9–19] and the references mentioned therein. Abbas *et al.* [20] proved some common fixed points in partially ordered metric spaces (see also [21]). Gu and He [22] proved some common fixed point results for self-maps with twice power type Φ-contractive condition. Recently, Gu and Zhang [23] obtained some common fixed point theorems for six self-mappings with twice power type contraction condition.

Throughout this paper, we assume that a nonempty set $X = V(G)$ is equipped with a partial metric p, a directed graph G has no parallel edge and G is a weighted graph in the sense that each vertex x is assigned the weight $p(x,x)$ and each edge (x,y) is assigned the weight $p(x,y)$. As p is a partial metric on X, the weight assigned to each vertex x need not be zero and whenever a zero weight is assigned to some edge (x,y), it reduces to a loop (x,x).

Also, the subset $W(G)$ of $V(G)$ is said to be complete if for every $x, y \in W(G)$, we have $(x,y) \in E(G)$.

Definition 1.4 Self-mappings f and g on X are said to form a power graphic contraction pair if

(a) for every vertex v in G, (v, fv) and $(v, gv) \in E(G)$,

(b) there exists $\phi : \mathbb{R}^+ \to \mathbb{R}^+$ an upper semi-continuous and nondecreasing function with $\phi(t) < t$ for each $t > 0$ such that

$$p^{\delta}(fx, gy) \leq \phi\bigl(p^{\alpha}(x,y)p^{\beta}(x,fx)p^{\gamma}(y,gy)\bigr) \tag{1.1}$$

for all $(x,y) \in E(G)$ holds, where $\alpha, \beta, \gamma \geq 0$ with $\delta = \alpha + \beta + \gamma \in (0, \infty)$.

If we take $f = g$, then the mapping f is called a power graphic contraction.

The aim of this paper is to investigate the existence of common fixed points of a power graphic contraction pair in the framework of complete partial metric spaces endowed with a graph. Our results extend and strengthen various known results [8, 12, 13, 24].

2 Common fixed point results

We start with the following result.

Theorem 2.1 *Let (X,p) be a complete partial metric space endowed with a directed graph G. If $f, g : X \to X$ form a power graphic contraction pair, then the following hold*:

(i) $F(f) \neq \emptyset$ *or* $F(g) \neq \emptyset$ *if and only if* $F(f) \cap F(g) \neq \emptyset$.

(ii) *If* $u \in F(f) \cap F(g)$, *then the weight assigned to the vertex* u *is* 0.

(iii) $F(f) \cap F(g) \neq \emptyset$ *provided that* G *satisfies the property* (A).

(iv) $F(f) \cap F(g)$ *is complete if and only if* $F(f) \cap F(g)$ *is a singleton.*

Proof To prove (i), let $u \in F(f)$. By the given assumption, $(u, gu) \in E(G)$. Assume that we assign a non-zero weight to the edge (u, gu). As $(u, u) \in E(G)$ and f and g form a power graphic contraction, we have

$$\begin{aligned} p^{\delta}(u,gu) &= p^{\delta}(fu,gu) \\ &\leq \phi\bigl(p^{\alpha}(u,u)p^{\beta}(u,fu)p^{\gamma}(u,gu)\bigr) \\ &= \phi\bigl(p^{\alpha+\beta}(u,u)p^{\gamma}(u,gu)\bigr) \\ &\leq \phi\bigl(p^{\alpha+\beta}(u,gu)p^{\gamma}(u,gu)\bigr) \\ &= \phi\bigl(p^{\delta}(u,gu)\bigr) \\ &< p^{\delta}(u,gu), \end{aligned}$$

a contradiction. Hence, the weight assigned to the edge (u, gu) is zero and so $u = gu$. Therefore, $u \in F(f) \cap F(g) \neq \emptyset$. Similarly, if $u \in F(g)$, then we have $u \in F(f)$. The converse is straightforward.

Now, let $u \in F(f) \cap F(g)$. Assume that the weight assigned to the vertex u is not zero, then from (1.1), we have

$$\begin{aligned} p^{\delta}(u,u) &= p^{\delta}(fu,gu) \\ &\leq \phi\bigl(p^{\alpha}(u,u)p^{\beta}(u,fu)p^{\gamma}(u,gu)\bigr) \\ &= \phi\bigl(p^{\alpha+\beta+\gamma}(u,u)\bigr) \\ &= \phi\bigl(p^{\delta}(u,u)\bigr) \\ &< p^{\delta}(u,u), \end{aligned}$$

a contradiction. Hence, (ii) is proved.

To prove (iii), we will first show that there exists a sequence $\{x_n\}$ in X with $fx_{2n} = x_{2n+1}$ and $gx_{2n+1} = x_{2n+2}$ for all $n \in \mathbb{N}$ with $(x_n, x_{n+1}) \in E(G)$, and $\lim_{n\to\infty} p(x_n, x_{n+1}) = 0$.

Let x_0 be an arbitrary point of X. If $fx_0 = x_0$, then the proof is finished, so we assume that $fx_0 \neq x_0$. As $(x_0, fx_0) \in E(G)$, so $(x_0, x_1) \in E(G)$. Also, $(x_1, gx_1) \in E(G)$ gives $(x_1, x_2) \in E(G)$. Continuing this way, we define a sequence $\{x_n\}$ in X such that $(x_n, x_{n+1}) \in E(G)$ with $fx_{2n} = x_{2n+1}$ and $gx_{2n+1} = x_{2n+2}$ for $n \in \mathbb{N}$.

We may assume that the weight assigned to each edge (x_{2n}, x_{2n+1}) is non-zero for all $n \in \mathbb{N}$. If not, then $x_{2k} = x_{2k+1}$ for some k, so $fx_{2k} = x_{2k+1} = x_{2k}$, and thus $x_{2k} \in F(f)$. Hence, $x_{2k} \in F(f) \cap F(g)$ by (i). Now, since $(x_{2n}, x_{2n+1}) \in E(G)$, so from (1.1), we have

$$\begin{aligned} p^{\delta}(x_{2n+1},x_{2n+2}) &= p^{\delta}(fx_{2n},gx_{2n+1}) \\ &\leq \phi\bigl(p^{\alpha}(x_{2n},x_{2n+1})p^{\beta}(x_{2n},fx_{2n})p^{\gamma}(x_{2n+1},gx_{2n+1})\bigr) \\ &= \phi\bigl(p^{\alpha}(x_{2n},x_{2n+1})p^{\beta}(x_{2n},x_{2n+1})p^{\gamma}(x_{2n+1},x_{2n+2})\bigr) \\ &= \phi\bigl(p^{\alpha+\beta}(x_{2n},x_{2n+1})p^{\gamma}(x_{2n+1},x_{2n+2})\bigr) \\ &< p^{\alpha+\beta}(x_{2n},x_{2n+1})p^{\gamma}(x_{2n+1},x_{2n+2}), \end{aligned}$$

which implies that

$$p^{\alpha+\beta}(x_{2n+1}, x_{2n+2}) < p^{\alpha+\beta}(x_{2n}, x_{2n+1}),$$

a contradiction if $\alpha + \beta = 0$. So, take $\alpha + \beta > 0$, and we have

$$p(x_{2n+1}, x_{2n+2}) < p(x_{2n}, x_{2n+1})$$

for all $n \in \mathbb{N}$. Again from (1.1), we have

$$\begin{aligned}
p^{\delta}(x_{2n+2}, x_{2n+3}) &= p^{\delta}(gx_{2n+1}, fx_{2n+2}) \\
&= p^{\delta}(fx_{2n+2}, gx_{2n+1}) \\
&\le \phi\big(p^{\alpha}(x_{2n+2}, x_{2n+1})p^{\beta}(x_{2n+2}, fx_{2n+2})p^{\gamma}(x_{2n+1}, gx_{2n+1})\big) \\
&= \phi\big(p^{\alpha}(x_{2n+1}, x_{2n+2})p^{\beta}(x_{2n+2}, x_{2n+3})p^{\gamma}(x_{2n+1}, x_{2n+2})\big) \\
&= \phi\big(p^{\alpha+\gamma}(x_{2n+1}, x_{2n+2})p^{\beta}(x_{2n+2}, x_{2n+3})\big) \\
&< p^{\alpha+\gamma}(x_{2n+1}, x_{2n+2})p^{\beta}(x_{2n+2}, x_{2n+3}),
\end{aligned}$$

which implies that

$$p^{\alpha+\gamma}(x_{2n+2}, x_{2n+3}) < p^{\alpha+\gamma}(x_{2n+1}, x_{2n+2}).$$

We arrive at a contradiction in case $\alpha + \gamma = 0$. Therefore, we must take $\alpha + \gamma > 0$; consequently, we have

$$p(x_{2n+2}, x_{2n+3}) < p(x_{2n+1}, x_{2n+2})$$

for all $n \in \mathbb{N}$. Hence,

$$p^{\delta}(x_n, x_{n+1}) \le \phi\big(p^{\delta}(x_{n-1}, x_n)\big) < p^{\delta}(x_{n-1}, x_n) \tag{2.1}$$

for all $n \in \mathbb{N}$. Therefore, the decreasing sequence of positive real numbers $\{p^{\delta}(x_n, x_{n+1})\}$ converges to some $c \ge 0$. If we assume that $c > 0$, then from (2.1) we deduce that

$$0 < c \le \limsup_{n\to\infty} \phi\big(p^{\delta}(x_{n-1}, x_n)\big) \le \phi(c) < c,$$

a contradiction. So, $c = 0$, that is, $\lim_{n\to\infty} p^{\delta}(x_n, x_{n+1}) = 0$ and so we have $\lim_{n\to\infty} p(x_n, x_{n+1}) = 0$. Also,

$$p^{\delta}(x_n, x_{n+1}) \le \phi\big(p^{\delta}(x_{n-1}, x_n)\big) \le \cdots \le \phi^{n}\big(p^{\delta}(x_0, x_1)\big). \tag{2.2}$$

Now, for $m, n \in \mathbb{N}$ with $m > n$,

$$\begin{aligned}
p^{\delta}(x_n, x_m) &\le p^{\delta}(x_n, x_{n+1}) + p^{\delta}(x_{n+1}, x_{n+2}) + \cdots + p^{\delta}(x_{m-1}, x_m) \\
&\quad - p^{\delta}(x_{n+1}, x_{n+1}) - p^{\delta}(x_{n+2}, x_{n+2}) - \cdots - p^{\delta}(x_{m-1}, x_{m-1}) \\
&\le \phi^{n}\big(p^{\delta}(x_0, x_1)\big) + \phi^{n+1}\big(p^{\delta}(x_0, x_1)\big) + \cdots + \phi^{m-1}\big(p^{\delta}(x_0, x_1)\big)
\end{aligned}$$

implies that $p^\delta(x_n, x_m)$ converges to 0 as $n, m \to \infty$. That is, $\lim_{n,m\to\infty} p(x_n, x_m) = 0$. Since (X, p) is complete, following similar arguments to those given in Theorem 2.1 of [9], there exists a $u \in X$ such that $\lim_{n,m\to\infty} p(x_n, x_m) = \lim_{n\to\infty} p(x_n, u) = p(u, u) = 0$. By the given hypothesis, $(x_{2n}, u) \in E(G)$ for all $n \in \mathbb{N}$. We claim that the weight assigned to the edge (u, gu) is zero. If not, then as f and g form a power graphic contraction, so we have

$$\begin{aligned} p^\delta(x_{2n+1}, u) &= p^\delta(fx_{2n}, gu) \\ &\le \phi\bigl(p^\alpha(x_{2n}, u)p^\beta(x_{2n}, fx_{2n})p^\gamma(u, gu)\bigr) \\ &= \phi\bigl(p^\alpha(x_{2n}, u)p^\beta(x_{2n}, x_{2n+1})p^\gamma(u, gu)\bigr). \end{aligned} \tag{2.3}$$

We deduce, by taking upper limit as $n \to \infty$ in (2.3), that

$$\begin{aligned} p^\delta(u, gu) &\le \limsup_{n\to\infty} \phi\bigl(p^\alpha(x_{2n}, u)p^\beta(x_{2n}, x_{2n+1})p^\gamma(u, gu)\bigr) \\ &\le \phi\bigl(p^\alpha(u, u)p^\beta(u, u)p^\gamma(u, gu)\bigr) \\ &\le \phi\bigl(p^{\alpha+\beta+\gamma}(u, gu)\bigr) \\ &< p^\delta(u, gu), \end{aligned}$$

a contradiction. Hence, $u = gu$ and $u \in F(f) \cap F(g)$ by (i).

Finally, to prove (iv), suppose the set $F(f) \cap F(g)$ is complete. We are to show that $F(f) \cap F(g)$ is a singleton. Assume on the contrary that there exist u and v such that $u, v \in F(f) \cap F(g)$ but $u \neq v$. As $(u, v) \in E(G)$ and f and g form a power graphic contraction, so

$$\begin{aligned} 0 &< p^\delta(u, v) = p^\delta(fu, fv) \\ &\le \phi\bigl(p^\alpha(u, v)p^\beta(u, fu)p^\gamma(v, gv)\bigr) \\ &= \phi\bigl(p^\alpha(u, v)p^\beta(u, u)p^\gamma(v, v)\bigr) \\ &\le \phi\bigl(p^\delta(u, v)\bigr), \end{aligned}$$

a contradiction. Hence, $u = v$. Conversely, if $F(f) \cap F(g)$ is a singleton, then it follows that $F(f) \cap F(g)$ is complete. □

Corollary 2.2 *Let (X, p) be a complete partial metric space endowed with a directed graph G. If we replace* (1.1) *by*

$$p^\delta\bigl(f^s x, g^t y\bigr) \le \phi\bigl(p^\alpha(x, y)p^\beta\bigl(x, f^s x\bigr)p^\gamma\bigl(y, g^t y\bigr)\bigr), \tag{2.4}$$

where $\alpha, \beta, \gamma \ge 0$ with $\delta = \alpha + \beta + \gamma \in (0, \infty)$ and $s, t \in \mathbb{N}$, then the conclusions obtained in Theorem 2.1 *remain true.*

Proof It follows from Theorem 2.1, that $F(f^s) \cap F(g^t)$ is a singleton provided that $F(f^s) \cap F(g^t)$ is complete. Let $F(f^s) \cap F(g^t) = \{w\}$, then we have $f(w) = f(f^s(w)) = f^{s+1}(w) = f^s(f(w))$, and $g(w) = g(g^t(w)) = g^{t+1}(w) = g^t(g(w))$ implies that fw and gw are also in $F(f^s) \cap F(g^t)$. Since $F(f^s) \cap F(g^t)$ is a singleton, we deduce that $w = fw = gw$. Hence, $F(f) \cap F(g)$ is a singleton. □

The following remark shows that different choices of α, β and γ give a variety of power graphic contraction pairs of two mappings.

Remarks 2.3 Let (X,p) be a complete partial metric space endowed with a directed graph G.

(R1) We may replace (1.1) with the following:

$$p^3(fx,gy) \le \phi\bigl(p(x,y)p(x,fx)p(y,gy)\bigr) \tag{2.5}$$

to obtain conclusions of Theorem 2.1. Indeed, taking $\alpha = \beta = \gamma = 1$ in Theorem 2.1, one obtains (2.5).

(R2) If we replace (1.1) by one of the following condition:

$$p^2(fx,gy) \le \phi\bigl(p(x,y)p(x,fx)\bigr), \tag{2.6}$$

$$p^2(fx,gy) \le \phi\bigl(p(x,y)p(y,gy)\bigr), \tag{2.7}$$

$$p^2(fx,gy) \le \phi\bigl(p(x,fx)p(y,gy)\bigr), \tag{2.8}$$

then the conclusions obtained in Theorem 2.1 remain true. Note that

(i) if we take $\alpha = \beta = 1$ and $\gamma = 0$ in (1.1), then we obtain (2.6),

(ii) take $\alpha = \gamma = 1$, $\beta = 0$ in (1.1) to obtain (2.7),

(iii) use $\beta = \gamma = 1$, $\alpha = 0$ in (1.1) and obtain (2.8).

(R3) Also, if we replace (1.1) by one of the following conditions:

$$p(fx,gy) \le \phi\bigl(p(x,y)\bigr), \tag{2.9}$$

$$p(fx,gy) \le \phi\bigl(p(x,fx)\bigr), \tag{2.10}$$

$$p(fx,gy) \le \phi\bigl(p(y,gy)\bigr), \tag{2.11}$$

then the conclusions obtained in Theorem 2.1 remain true. Note that

(iv) take $\alpha = 1$ and $\beta = \gamma = 0$ in (1.1) to obtain (2.9),

(v) to obtain (2.10), take $\beta = 1$, $\alpha = \gamma = 0$ in (1.1),

(vi) if one takes $\gamma = 1$, $\alpha = \beta = 0$ in (1.1), then we obtain (2.11).

Remark 2.4 If we take $f = g$ in a power graphic contraction pair, then we obtain fixed point results for a power graphic contraction.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
All authors read and approved the final manuscript.

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