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# Coincidence fixed point results for $(\Theta, g)_b$ -contraction maps

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## Abstract

With the establishment of a new contraction known as fuzzy- $(\Theta, g)_b$ -contraction, the primary goal of this work is to elaborate and develop an understanding of this new class of fuzzy contractive mappings and to investigate some coincidence point results by using  $(\Theta, g)_b$ -contractive setup. We establish certain conditions for the existence and uniqueness of fuzzy points of coincidence in fuzzy  $b$ -metric spaces.

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## 1. INTRODUCTION

Numerous research projects have focused on the analysis of fixed points (FPs) of mappings satisfying contraction conditions due to their broad range of applicability in various domains. In this regard, a number of authors in the field of metric fixed point (FP) theory have drawn inspiration from the traditional results of Banach [2] and Edelstein [8].

In the work of Kramosil and Michalek [16], Grabiec [10]-who paved the way for introducing fixed point (FP) theory in fuzzy metric spaces (FMS)-expanded on the findings of Banach [2] and Edelstein [8] within the fuzzy framework. By adding the concept of completeness of FMS, George and Veeramani [9] extended the FP outcomes that Grabiec proposed in his work [10]. Numerous authors studied and analyzed unique contractions within FMS, yielding practical outcomes. (See [17], [22], [23], [11], [12]). Jain *et al.* [15] introduced the concept of compatibility on which more comprehensive research was conducted incorporating well-known previous contractions and classes by many authors ([11], [17], [22], and [23]). In recent years, several authors have taken alternative approaches and considered different kinds of mappings and metric spaces (fuzzy or non-fuzzy) ([13], [6], [5]).

Bakhtin [1] and Czerwik ([3], [4]) initially introduced b-metric spaces as a generalization of metric spaces that relaxes the triangular inequality. Then, fuzzy b-metric space was introduced by Hussain *et al.* [14], who also obtained certain fixed

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point theorems. Nădăban [18] shortly afterward introduced another version that differs slightly from the one provided by Hussain *et al.* [14] and investigated some of its topological characteristics along with some decomposition results. Further development of this idea was done using more broadly defined contractive conditions (see [19], [20], [14]).

In this study, we present the notion of fuzzy- $(\Theta, g)_b$ -contraction by considering a family of functions that satisfy some specific properties. We also establish some findings about the uniqueness and existence of coincidence points for such contractions in the setting of fuzzy b-metric spaces.

## 2. ELEMENTARY INTERPRETATIONS

*Definition 2.1.* [21] A binary relation  $\star : [0, 1] \times [0, 1] \rightarrow [0, 1]$ , meeting the following requirements:

- (1)  $h \star 1 = h$ ;
- (2)  $h \star l = l \star h$ ;
- (3)  $(e \star l) \star h = (e \star l) \star h$ ;
- (4)  $h \star k \leq e \star l, \forall h, k, e, l \in [0, 1]$ .

is a continuous t-norm.

*Definition 2.2.* [9] For a set  $\check{W}$  and a fuzzy set  $\check{M}$  in  $\check{W} \times \check{W} \times [0, \infty]$ ; a triplet  $(\check{W}, \check{M}, \star)$  is a fuzzy metric space if it meets the following requirements:

- (1)  $\check{M}(h, w, r) \geq 0$ ,
- (2)  $\check{M}(h, w, r) = 1 \forall r > 0 \Leftrightarrow h = w$ ,
- (3)  $\check{M}(h, w, r) = \check{M}(w, h, r)$ ,
- (4)  $\check{M}(h, l, r+k) \leq \check{M}(h, w, r) \star \check{M}(w, l, k)$ ,
- (5)  $\check{M}(h, w, \cdot) : (0, \infty) \rightarrow [0, 1]$  is left-continuous,  $\forall h, w, l \in \check{W}$  and  $r, k > 0$ .

and it is called a FMS.

LEMMA 2.3. [10]  $\check{M}(h, w, \cdot)$  is increasing,  $\forall h, w \in \check{W}$ .

*Definition 2.4.* [9] For a FMS  $(\check{W}, \check{M}, \star)$ ,

- (1) a sequence  $\{\check{k}_p\} \subseteq \check{W}$  is  $\check{M}$ -Cauchy if  $\forall \varepsilon \in ]0, \infty[$ ,  $r > 0$ ,  $\exists p_0 \in \mathbb{N}$  such that  $\check{M}(\check{k}_l, \check{k}_p, r) > 1 - \varepsilon \forall l \geq p_0$ .
- (2)  $\{\check{k}_p\} \subseteq \check{W}$  converges to  $k \in \check{W}$  if  $\lim_{p \rightarrow \infty} \check{M}(\check{k}_p, k, r) = 1$  for  $r > 0$ .

(3) each  $\check{M}$ -Cauchy sequence, if converges in  $\check{W}$ , then  $\check{W}$  is called  $\check{M}$ -complete.

*Definition 2.5.* ([1], [4]) For set  $\mathscr{W}$  and map  $B: \mathscr{W} \times \mathscr{W} \rightarrow [0, +\infty[$ , if the following axioms hold for  $w, h, l \in \mathscr{W}$ :

- (b<sub>1</sub>)  $\mathfrak{B}(w, h) = 0 \Leftrightarrow w = h$ ;
- (b<sub>2</sub>)  $\mathfrak{B}(w, h) = \mathfrak{B}(h, w)$ ;
- (b<sub>3</sub>)  $\mathfrak{B}(w, h) \leq b_m(\mathfrak{B}(w, l) + \mathfrak{B}(l, h)) \quad (b_m \geq 1)$ .

Then  $\mathfrak{B}$  is called a  $b$ -metric and the space is symbolized by  $(\mathscr{W}, \mathfrak{B})$ .

*Definition 2.6.* [18] For a set  $\check{W}$ , fuzzy set  $\check{M}$  in  $\check{W} \times \check{W} \times [0, \infty]$  and  $b_m \geq 1$ ; a triplet  $(\check{W}, \check{M}, \star)$  is a fuzzy b-metric space (FbMS) if it meets the following requirements:

- (1)  $\check{M}(h, w, r) \geq 0$ ,
- (2)  $\check{M}(h, w, r) = 1 \forall r > 0 \Leftrightarrow h = w$ ,
- (3)  $\check{M}(h, w, r) = \check{M}(w, h, r)$ ,
- (4)  $\check{M}(h, l, b_m(r+k)) \leq \check{M}(h, w, r) \star \check{M}(w, l, k)$ ,
- (5)  $\check{M}(h, w, \cdot): (0, \infty) \rightarrow [0, 1]$  is left continuous,  $\forall h, w, l \in \check{W}$  and  $r, k > 0$ .

*Definition 2.7.* [18] For a FbMS  $(\check{W}, \check{M}, \star, b_m \geq 1)$ ,

- (1) a sequence  $\{\check{k}_p\} \subseteq \check{W}$  is  $\check{M}_{b_m}$ -Cauchy if  $\forall \varepsilon \in ]0, \infty[$ ,  $r > 0$ ,  $\exists p_0 \in \mathbb{N}$  such that  $\check{M}(\check{k}_l, \check{k}_p, b_m r) > 1 - \varepsilon \forall l \geq p_0$ .
- (2)  $\{\check{k}_p\} \subseteq \check{W}$  converges to  $k \in \check{W}$  if  $lt_{p \rightarrow \infty} \check{M}(\check{k}_p, k, b_m r) = 1$  for  $r > 0$ .
- (3) each  $\check{M}_{b_m}$ -Cauchy sequence, if converges in  $\check{W}$ , then  $\check{W}$  is called  $\check{M}_{b_m}$ -complete.

*Definition 2.8.* [15] For a FMS  $(\check{W}, \check{M}, \star)$ , two maps  $\rho, \zeta$  are compatible if

$$\lim_{p \rightarrow \infty} \check{M}(\rho \zeta w_p, \zeta \rho w_p, r) = 1$$

for  $r > 0$ , whenever for  $\{w_r\} \subseteq \check{W}$ , we have  $\lim_{p \rightarrow \infty} \rho w_p = \lim_{p \rightarrow \infty} \zeta w_p = w \in \check{W}$ .

*Definition 2.9.* [15] The maps  $\rho$  and  $\zeta$  are weakly compatible if  $\rho w = \zeta w$  for  $w \in \check{W} \Rightarrow \rho \zeta w = \zeta \rho w$ .

*Remark 2.10.* [15] For two weakly compatible maps  $\rho$  and  $\zeta$ ; if there exists a single coincident point  $l$ , then  $l$  is a single common fixed point of  $\rho$  and  $\zeta$ .

### 3. NEW FINDINGS

*Definition 3.1.* Consider the collection of functions  $\zeta : (0, 1] \times (0, 1] \rightarrow \mathbb{R}$  satisfying,

$$\zeta(r, k) > k, \forall r, k \in (0, 1). \quad (1)$$

Denote it by  $\Theta$ . Clearly,  $\zeta(k, k) > k$  for  $k \in (0, 1)$ .

EXAMPLE 3.2. Following are the examples for above collection:

- (1)  $\zeta(r, k) = \phi(k)$ , where  $\phi : ]0, 1] \rightarrow ]0, 1]$  is such that  $\phi(k) > k$ , for  $k \in (0, 1)$ ;
- (2)  $\zeta(r, k) = \frac{k}{r}$ ;
- (3)  $\zeta(r, k) = r + \frac{1}{k+1}$ .

*Definition 3.3.* Let  $\varpi, g : \check{W} \rightarrow \check{W}$  be two maps on FbMS  $(\check{W}, \check{M}, *, b_m \geq 1)$  and  $\exists \zeta \in \Theta$  such that,

$$\check{M}(\varpi h, \varpi w, b_m r) \geq \zeta(\check{M}(\varpi h, \varpi w, r), \check{M}(gh, gw, b_m r)), \quad (2)$$

for  $h, w \in \check{W}$ ,  $\varpi h = \varpi w$ ,  $gh \neq gw$ ,  $r > 0$ . Then  $\varpi$  is called  $(\Theta, g)_b$ -fuzzy-contraction map w.r.t.  $\zeta \in \Theta$ .

*Definition 3.4.* Let  $\varpi : \check{W} \rightarrow \check{W}$  be a map on FbMS  $(\check{W}, \check{M}, *, b_m \geq 1)$  and  $\exists \zeta \in \Theta$ . Then,  $(\check{W}, \check{M}, \varpi, \zeta)$  has  $\mathfrak{R}$ -property, if for a sequence  $\{k_p\}$  set initially as  $w \in \check{W}$ , i.e.,  $k_p = \varpi^p w$ ,  $\forall p \in \mathbb{N}$  with

$$\begin{aligned} \mathfrak{R} : \inf_{q > p} \check{M}(k_p, k_q, b_m r) &\leq \inf_{q > p} \check{M}(k_{p+1}, k_{q+1}, b_m r), \forall p \in \mathbb{N}, r > 0 \\ \Rightarrow \liminf_{p \rightarrow \infty, q > p} \zeta(\check{M}(k_{p+1}, k_{q+1}, r), \check{M}(k_p, k_q, b_m r)) &= 1 \forall r > 0. \end{aligned} \quad (3)$$

THEOREM 3.5. Let  $(\check{W}, \check{M}, *, b_m \geq 1)$  be a FbMS,  $\varpi, g : \check{W} \rightarrow \check{W}$  be two maps,  $\varpi$  a

$(\Theta, g)_b$ -fuzzy contraction and  $(\check{W}, \check{M}, \varpi, \zeta)$  has  $\mathfrak{K}$ -property. Assume that,

- (1)  $\varpi(\check{W})$  or  $g(\check{W})$  is complete, or
- (2)  $g$  is continuous,  $\check{W}$  is complete,  $\varpi, g$  commute, or
- (3)  $g$  is continuous,  $\check{W}$  is complete,  $\varpi, g$  are compatible.

Then  $\varpi$  and  $g$  admit a single coincident point.

Proof. Let  $h_1$  and  $h_2$  be two coincident points of  $\varpi$  and  $g$ . Consequently, there exist  $l_1$  and  $l_2$  such that  $\varpi(l_1) = g(l_1) = h_1$  and  $\varpi(l_2) = g(l_2) = h_2$ .

Using (1) and (2), we obtain

$$\begin{aligned} \check{M}(h_1, h_2, b_m r) &= \check{M}(\varpi l_1, \varpi l_2, b_m r) \\ &\geq \zeta(\check{M}(\varpi l_1, \varpi l_2, r), \check{M}(g l_1, g l_2, b_m r)) \\ &> \check{M}(g l_1, g l_2, b_m r) \\ &= \check{M}(h_1, h_2, b_m r) \end{aligned}$$

which is contradictory.

Choose a sequence  $\{k_p\}$  such that  $k_p = \varpi^p w = \varpi w_p = g w_{p+1}$  where  $p \in \mathbb{N} \cup \{0\}$ . If  $k_{p_0} = k_{p_0+1}$  for some  $p_0 \in \mathbb{N} \cup \{0\}$ , then  $g w_{p_0+1} = k_{p_0} = k_{p_0} + 1 = \varpi w_{p_0+1}$ . Thus,  $g$  and  $\varpi$  have a coincident point. Therefore, let  $k_p \neq k_{p+1}$  for  $p \in \mathbb{N} \cup \{0\}$ .

Now,

$$\begin{aligned} \check{M}(k_{p+1}, k_{p+2}, b_m r) &= \check{M}(\varpi w_{p+1}, \varpi w_{p+2}, b_m r) \\ &\geq \zeta(\check{M}(\varpi w_{p+1}, \varpi w_{p+2}, b_m r), \check{M}(g w_{p+1}, g w_{p+2}, r)) \\ &> \check{M}(g w_{p+1}, g w_{p+2}, b_m r) \\ &= \check{M}(k_p, k_{p+1}, b_m r). \end{aligned} \tag{4}$$

which gives

$$\check{M}(k_p, k_{p+1}, b_m r) < \check{M}(k_{p+1}, k_{p+2}, b_m r) \quad \forall r > 0.$$

If  $k_p = k_h$  for  $p < h$ , then  $k_{p+1} = \varpi w_{p+1} = \varpi w_{h+1} = k_{h+1}$ .

Using (2) and (4), we obtain

$$\check{M}(k_p, k_{p+1}, b_m r) < \check{M}(k_h, k_{h+1}, b_m r) = \check{M}(\check{M}(k_p, k_{p+1}, b_m r)), \forall r > 0.$$

which is contradictory. Therefore, let  $k_p \neq k_h$  for  $h, p \in \mathbb{N}$ .

Now, for  $r > 0$ , let

$$\alpha_p(r) = \inf_{h > p} \check{M}(k_p, k_h, b_m r),$$

and consider

$$\begin{aligned} \check{M}(k_{p+1}, k_{h+1}, b_m r) &= \check{M}(\varpi w_{p+1}, \varpi w_{h+1}, b_m r) \\ &\geq \zeta(\check{M}(\varpi w_{p+1}, \varpi w_{h+1}, r), \check{M}(g w_{p+1}, g w_{h+1}, b_m r)) \\ &> \check{M}(g w_{p+1}, g w_{h+1}, b_m r) \\ &= \check{M}(k_p, k_h, b_m r), \forall r > 0. \end{aligned} \tag{5}$$

Hence,  $\check{M}(k_p, k_h, b_m r) < \check{M}(k_{p+1}, k_{h+1}, b_m r)$ ,  $\forall h > p$ ,

which implies

$$\inf_{h > p} \check{M}(k_p, k_h, b_m r) \leq \inf_{h > p} \check{M}(k_{p+1}, k_{h+1}, b_m r),$$

i.e.  $\alpha_p(r) \leq \alpha_{p+1}(r) \forall p \in \mathbb{N}$ .

So,  $\{\alpha_p(r)\}_{r > 0}$  is bounded and monotonic. We claim that  $\lim_{p \rightarrow \infty} \alpha_p(r) = 1$ ,  $\forall r > 0$ .

Let  $\lim_{p \rightarrow \infty} \alpha_p(\hat{r}) = \alpha(\hat{r}) < 1$  for  $0 < \hat{r} < r$ . As  $(\check{W}, \check{M}, \varpi, \zeta)$  has the  $\mathfrak{R}$ -property, (and since  $k_p = \varpi^p(w)$ ,  $w \in \check{W}$ ), we have

$$\liminf_{p \rightarrow \infty} \inf_{h > p} \check{M}(k_{p+1}, k_{h+1}, b_m \hat{r}), \check{M}(k_p, k_h, b_m \hat{r}) = 1. \tag{6}$$

Now,

$$\begin{aligned} \inf_{h > p} \check{M}(k_{p+1}, k_{h+1}, b_m \hat{r}) &\geq \inf_{h > p} \zeta(\check{M}(\varpi w_{p+1}, \varpi w_{h+1}, \hat{r}), \check{M}(g w_{p+1}, g w_{h+1}, b_m \hat{r})) \\ \Rightarrow \inf_{h > p} \check{M}(k_{p+1}, k_{h+1}, b_m \hat{r}) &\geq \inf_{h > p} \zeta(\check{M}(k_{p+1}, k_{h+1}, \hat{r}), \check{M}(k_p, k_h, b_m \hat{r})) \\ &\geq \inf_{h > p} \check{M}(k_p, k_h, b_m \hat{r}) \end{aligned}$$

i.e.  $\alpha_{p+1}(\hat{r}) \geq \alpha_p(\hat{r})$ .

Taking  $p \rightarrow \infty$  and by (6), we get  $\alpha(\hat{r}) = 1$  which is again a contradiction. Therefore,

$$\liminf_{p \rightarrow \infty, h > p} \check{M}(k_p, k_h, b_m r) = 1, \forall r > 0.$$

Thus, formation of  $a_p$  gives

$$\lim_{p, h \rightarrow \infty} \check{M}(k_p, k_h, b_m r) = 1, \forall r > 0.$$

which shows  $\{k_p\}$  is  $\check{M}_{b_m}$ -Cauchy.

Now, assume that  $g(\check{W})$  is complete.

As  $\{k_p\} \subseteq g(\check{W})$ , let  $k_p \rightarrow gv$  i.e.  $gk_p \rightarrow gv$  as  $p \rightarrow \infty, v \in \check{W}$ . Now, we claim that  $\varpi v = gv$ .

Clearly,  $k_p \neq \varpi v = gv$ . By (2) and formation of  $\zeta$ ,

$$\check{M}(gw_p, gv, b_m r) < \zeta(\check{M}(\varpi w_p, \varpi v, b_m r), \check{M}(gw_p, gv, b_m r)) \leq \check{M}(gw_p, gv, b_m r).$$

Taking  $p \rightarrow \infty$  gives

$$\begin{aligned} \check{M}(gv, gv, b_m r) &\leq \check{M}(\varpi w_p, \varpi v, b_m r) \\ &\Rightarrow 1 \leq \lim_{p \rightarrow \infty} \check{M}(\varpi w_p, \varpi v, b_m r). \end{aligned}$$

Therefore,  $\varpi w_p \rightarrow \varpi v$  as  $p \rightarrow \infty$  that implies  $k_p \rightarrow \varpi v$  as  $p \rightarrow \infty$ .

Also, the uniqueness of the limit implies  $\varpi v = gv$ . Thus,  $v$  is a single coincident point of  $\varpi$  and  $g$ . Similarly, it can be proved that  $v$  is a single coincident point of  $\varpi$  and  $g$  when  $\varpi(\check{W})$  is complete.

Now, assume that condition (2) of Theorem holds: By completeness of  $\check{W}$ , there exists  $v \in \check{W}$  such that  $k_p \rightarrow v \Rightarrow gw_p \rightarrow v$  as  $p \rightarrow \infty$ . Again, as  $g$  is continuous,  $g^2 w_p \rightarrow g$  as  $p \rightarrow \infty$ .

Equation (2) and formation of  $\zeta$  gives

$$\check{M}(gw_p, gv, b_m r) \leq \zeta(\check{M}(\varpi(gw_p), \varpi v, r), \check{M}(g(gw_p), gv, b_m r)) \leq \check{M}(\varpi(gw_p), \varpi v, b_m r).$$

Taking  $p \rightarrow \infty$  gives

$$\begin{aligned} \check{M}(g\nu, g\nu, b_m r) &\leq \lim_{p \rightarrow \infty} \check{M}(\varpi g w_p, \varpi \nu, b_m r) \\ &= \lim_{p \rightarrow \infty} \check{M}(g \varpi w_p, \varpi \nu, b_m r) \\ &\Rightarrow 1 \leq \lim_{p \rightarrow \infty} \check{M}(g \varpi w_p, \varpi \nu, b_m r). \end{aligned}$$

Thus,  $g \varpi w_p \rightarrow \varpi \nu$  as  $p \rightarrow \infty$ . But the formation of  $k_p$  gives  $g \varpi w_p = g g w_{p+1} = g^2 w_{p+1}$  and the result is proved *i.e.*  $\varpi \nu = g\nu$  is a single coincident point of  $\varpi$  and  $g$ .

Now, assume that condition (3) of Theorem holds:

By the property of completeness of  $\check{W}$ ,  $\exists \nu \in \check{W}$  with  $k_p \rightarrow \nu \Rightarrow g w_p \rightarrow \nu$  as  $p \rightarrow \infty$ .

Also, continuity of  $g$  implies  $g \varpi w_p = g\nu$  as  $p \rightarrow \infty$ .

Using equation (2) and by formation of  $\zeta$  and  $g \varpi w_p = g g w_{p+1} = g^2 w_{p+1}$ , we obtain

$$\begin{aligned} \check{M}(g \varpi w_{p-1}, g\nu, b_m r) &= \check{M}(g(g w_p), g\nu, b_m r) \\ &= \zeta(\check{M}(\varpi(g w_p), \varpi \nu, r), \check{M}(g(g w_p), g\nu, b_m r)) \\ &\leq \check{M}(\varpi(g w_p), g\nu, b_m r). \end{aligned}$$

Taking  $p \rightarrow \infty$ ,

$$\check{M}(g\nu, g\nu, b_m r) \leq \lim_{p \rightarrow \infty} \check{M}(\varpi(g w_p), \varpi \nu, b_m r) \Rightarrow 1 \leq \lim_{p \rightarrow \infty} \check{M}(\varpi g w_p, \varpi \nu, b_m r).$$

So,  $\varpi \nu w_p \rightarrow \varpi \nu$  as  $p \rightarrow \infty$ . As  $\varpi, g$  are compatible, we get

$$\check{M}(\varpi g w_p, g \varpi w_p, b_m r) = 1, \quad r > 0.$$

Now, consider

$$\check{M}(\varpi \nu, g\nu, b_m r) \leq \check{M}(\varpi \nu, \varpi g w_p, b_m \frac{r}{3}) * \check{M}(\varpi g w_p, g \varpi w_p, b_m \frac{r}{3}) * \check{M}(g \varpi w_p, g\nu, b_m \frac{r}{3}).$$

Taking  $p \rightarrow \infty$  gives  $\varpi \nu = g\nu$  which proves that  $\varpi$  and  $g$  admit a single coincident point.

#### 4. ILLUSTRATION

In this section, some examples are provided to reinforce the established theorems.

Consider the sequence  $\{h_p\}_{p \in \mathbb{N}}$ . Let  $\check{W} = [0, 1]$  and the fuzzy set  $\check{M}$  be defined as  $\check{M}(h, w, r) = \frac{r}{r+|h-w|}$ . Then,  $(\check{W}, \check{M}, *)$  is a complete FMS. Let  $\zeta : ]0, 1[ \times ]0, 1[ \rightarrow \mathbb{R}$  and the maps  $\varpi, g$  are defined as

$$\zeta(k, r) = \frac{k}{r} \quad \forall r, k \in ]0, 1[;$$

$$\varpi h = \begin{cases} 0, & h \in [0, \frac{1}{4}] \\ 0.3, & h \in ]\frac{1}{4}, \frac{1}{2}[ \\ 0.2, & h \in [\frac{1}{2}, 1] \end{cases}$$

and

$$gh = \begin{cases} 0.3, & h \in [0, \frac{1}{4}] \\ 0.4, & h \in ]\frac{1}{4}, \frac{1}{2}[ \\ 0.6, & h \in [\frac{1}{2}, 1]. \end{cases}$$

Then,  $\zeta \in \Theta$  and  $(\check{W}, \check{M}, \varpi, \zeta)$  has  $\mathfrak{K}$ -property. Also,  $\varpi$  is a  $(\Theta, g)_b$ -Fuzzy contractive map w.r.t.  $\zeta$ . Thus, all the requirements of above result are met. So,  $\varpi$  and  $g$  have a single coincident point  $h = 0$ .

#### CONFLICT OF INTEREST

Regarding the subject matter of this paper, the authors have no conflicts of interest to disclose.

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