1. INTRODUCTION

In 1966, Imai and Iséki introduced the concept of $BCK/BCI$-algebras, which is a generalization of propositional calculus and the set-theoretic difference. The literature on the theory of $BCK/BCI$-algebras has been developed since then, and more focus has been placed on the ideal theory of $BCK/BCI$-algebras in particular. In $BCK/BCI$-algebras and other related algebraic structures, different kinds of concepts were investigated in various ways (see, e.g., [1–8]).

The fuzzy set theory proposed by Zadeh [9] has been extended to a lot of areas. In addition, a variety of extensions and generalizations of fuzzy sets have been introduced such as the following well known sets: bipolar fuzzy sets, hesitant fuzzy sets, intuitionistic fuzzy sets, interval-valued fuzzy sets and fuzzy multisets, etc. The interval-valued fuzzy set introduced by Zadeh takes the values of the membership functions as intervals instead of numbers. The study of interval-valued fuzzy algebraic structures started in [10] by introducing the concept of interval-valued fuzzy subgroups. Jun [11] extended the concept of interval-valued fuzzy sets to $BCK/BCI$-algebras and introduced the notions of interval-valued subalgebras and ideals. After that, the notion of interval-valued fuzzy sets in $BCK/BCI$-algebras with different aspects has been studied by several authors, for example, see [12–14].

Zhang introduced the notion of bipolar fuzzy sets which permits the membership degree of an element over two intervals $[-1, 0]$ and $[0, 1]$, that is, every element assigns negative and positive degree of memberships. By applying the notion of bipolar fuzzy sets to $BCK/BCI$-algebras, Lee [15] introduced the notions of bipolar fuzzy subalgebra and bipolar fuzzy ideal of $BCK/BCI$-algebras. Using $(\alpha, \beta)$-bipolar fuzzy generalized bi-ideals, Ibar et al. [16] characterized regular ordered semigroups whereas Bashir et al. [17] characterized the regular ordered ternary semigroups. For more related concepts on bipolar fuzzy sets, we refer to [18–22].

As in many problems, information often comes from several variables and there are often multi-attribute data that cannot be handled using current theories, a lot of approaches have been done to solve this problem. For example, Chen et al. [23] presented the $m$-polar fuzzy set, an expansion of the bipolar fuzzy set and as a new approach Akram et al. [24] introduced a technique in decision making based on $m$-polar fuzzy sets.

The $m$-polar fuzzy algebraic structures study began with the concept of $m$-polar fuzzy Lie subalgebras [25]. After that, the theory of $m$-polar fuzzy Lie ideals was studied in Lie algebras [26]. The concept of the $m$-polar fuzzy Lie groups was given in [27]. Moreover, $m$-polar fuzzy matroids have been studied in [28]. Further, $m$-polar fuzzy sets have been studied in different areas (see [29–33]). Recently, Al-Masarwah and Ahmad introduced the notion of $m$-polar fuzzy (commutative) ideals [34] and $m$-polar $(\alpha, \beta)$-fuzzy ideals [35] in $BCK/BCI$-algebras. As a continues work they introduced a new form of generalized $m$-polar fuzzy ideals in [36] and studied normalization of $m$-polar fuzzy subalgebras in [37]. A new advanced extensions are formed by merging two fuzzy information in one set as neutrosophic bipolar fuzzy sets, bipolar valued hesitant fuzzy sets and interval-valued $m$-polar fuzzy sets.

---

*Corresponding author. Email: chishtygm@gmail.com
Further, $\xi$ is called a fuzzy commutative ideal if $\xi(0) \geq \xi(v)$ and $\xi(v \ast (k \ast (k \ast v))) \geq \xi((v \ast k) \ast h) \wedge \xi(h)$.

By the interval number $\bar{n}$, we mean an interval denoted as $[n^-, n^+]$, where $0 \leq n^- \leq n^+ \leq 1$. We write $S[0, 1]$ to denote the set of all interval numbers. The interval $[n, n]$ is indicated by the index $n \in [0, 1]$ for whatever follows. For the interval numbers $\bar{n}_i = [n^+_i, n^-_i]$, $\bar{m}_i = [m^+_i, m^-_i] \in S[0, 1], i \in I$, we describe

(a) $\bar{n}_i \wedge \bar{m}_i = [n^+_i \cap m^+_i, n^-_i \cap m^-_i]$;
(b) $\bar{n}_i \vee \bar{m}_i = [n^+_i \cup m^+_i, n^-_i \cup m^-_i]$;
(c) $\bar{n}_i \leq \bar{n}_j \Leftrightarrow n^+_i \leq n^+_j \text{ and } n^-_i \leq n^-_j$;
(d) $\bar{n}_i = \bar{n}_j \Leftrightarrow n^+_i = n^+_j \text{ and } n^-_i = n^-_j$.

Let $X$ be a BCK/BCI-algebra. A mapping $\bar{\varepsilon} : X \to S[0, 1]$ is an interval-valued fuzzy set (briefly, IVF set) of $X$, where for all $v \in X, \bar{\varepsilon}(v) = \bar{\varepsilon}^-(v)$, $\bar{\varepsilon}^+$ and $\bar{\varepsilon}^*$ are fuzzy sets of $X$ with $\bar{\varepsilon}^-(v) \leq \bar{\varepsilon}^+(v)$.

An IVF set is called an IVF subalgebra if $(\forall \nu, \kappa \in X) \bar{\varepsilon}(v \ast (\kappa \ast \nu)) \geq \bar{\varepsilon}(\nu) \wedge \bar{\varepsilon}(\kappa)$ and it is called an IVF ideal if $\bar{\varepsilon}(0) \geq \bar{\varepsilon}(v)$ and $\bar{\varepsilon}(v) \geq (\nu \ast (\kappa \ast \nu)) \wedge \bar{\varepsilon}(\nu \ast (\kappa \ast \nu)) \forall \nu, \kappa \in X$. Moreover, $\bar{\varepsilon}$ is called an IVF commutative ideal if $\bar{\varepsilon}(0) \geq \bar{\varepsilon}(v)$ and $\bar{\varepsilon}(v \ast (\kappa \ast \nu)) \geq \bar{\varepsilon}((\nu \ast (\kappa \ast \nu))) \wedge \bar{\varepsilon}(\nu \ast (\kappa \ast \nu)) \forall \nu, \kappa \in X$.

3. INTERVAL-VALUED $m$-POLAR FUZZY SUBALGEBRAS

The notion of an IVmPF subalgebra in BCK/BCI-algebras is introduced and characterized in terms of subalgebra and fuzzy subalgebra of BCK/BCI-algebras.

Definition 3.1. Let $X$ be a nonempty set. An IVmPF set of $X$ is a mapping $\bar{\varepsilon} : X \to S[0, 1]^m$ defined as

$$\bar{\varepsilon}(v) = (\bar{\varepsilon}_1 \circ \bar{\varepsilon}(v), \bar{\varepsilon}_2 \circ \bar{\varepsilon}(v), \ldots, \bar{\varepsilon}_m \circ \bar{\varepsilon}(v))$$

where for $i \in \{1, 2, \ldots, m\}$, $\bar{\varepsilon}_i \circ \bar{\varepsilon} : X \to S[0, 1]$ is the $i$th-projection mapping.

That is,

$$\bar{\varepsilon}(v) = (\bar{\varepsilon}_1(v), \bar{\varepsilon}_2(v), \ldots, \bar{\varepsilon}_m(v))$$

for all $v \in X$. $\bar{\varepsilon}_i$ and $\bar{\varepsilon}_i^+$ are fuzzy sets of $X$ with $\bar{\varepsilon}_i(v) \leq \bar{\varepsilon}_i^+(v)$ for all $v \in X$ and $i \in \{1, 2, \ldots, m\}$.

We define an order relation on $S[0, 1]^m$ as pointwise, that is,

$$v \leq \kappa \iff \bar{\varepsilon}_i(v) \leq \bar{\varepsilon}_i(\kappa)$$

where $\bar{\varepsilon}_i : S[0, 1]^m \to S[0, 1]$ is the $i$th-projection mapping and $i \in \{1, 2, \ldots, m\}$. For an element $[a, b] \in S[0, 1]^m$, we mean that $([a, b], [a, b], \ldots, [a, b])$, while the element $[a, b] = ([a_1, b_1], [a_2, b_2], \ldots, [a_m, b_m])$ represents an arbitrary element of $S[0, 1]^m$. Clearly, the elements $[0, 0]$ and $[1, 1]$ are the smallest and largest elements in $S[0, 1]^m$. 

(IVmPF). For some recent work on these extensions, we refer the reader to [38–43].

The power of the theory of IVmPF as an advanced extension with all the work done on different algebraic structure motivated the authors to apply the theory of IVmPF on BCK/BCI-algebras. The novelty in this study lies in using the proposed model on BCK/BCI-algebras. The authors introduced and investigated the notions of interval-valued $m$-polar fuzzy subalgebras, interval-valued $m$-polar fuzzy ideals and interval-valued $m$-polar fuzzy commutative ideals in Sections 3, 4, 5, respectively. A summary of proposed and future work were given in Section 6.
Definition 3.2. An IVmPF set $\widehat{G}$ of $X$ is called an IVmPF subalgebra if
\[(\forall v, \kappa \in X) \widehat{G} (v \ast \kappa) \geq \widehat{G} (v) \land \widehat{G} (\kappa),\]
that is,
\[(\forall v, \kappa \in X, i \in \{1, 2, \ldots, m\}) \widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast \kappa) \geq \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa).\]

Example 1.
Consider a BCK-algebra in which $X = \{\emptyset, \varphi, \kappa, \ell\}$ and $*$ is given by the following table:

| $*$ | 0 | \emptyset | \varphi | \kappa | \ell |
|-----|---|---------|-------|------|-----|
| 0   | 0 | \emptyset | \varphi | \kappa | \ell |
| \emptyset | \emptyset | \varphi | \kappa | \ell |
| \varphi | \varphi | \varphi | \kappa | \ell |
| \kappa | \kappa | \kappa | \kappa | \ell |
| \ell | \ell | \ell | \ell | \ell |

Let $[\alpha, \varphi] = ([\alpha_1, \beta_1], [\alpha_2, \beta_2], \ldots, [\alpha_m, \beta_m]), [\alpha, \beta] = ([\alpha_1, \beta_1], [\alpha_2, \beta_2], \ldots, [\alpha_m, \beta_m]) \in S[0,1]^m$ such that $[\alpha, \varphi] \geq [\alpha, \beta]$. Now define an IVmPF set $\widehat{G}$ on $X$ as
\[
\widehat{G} (v) = \begin{cases} 
([\alpha_1, \beta_1], [\alpha_2, \beta_2], \ldots, [\alpha_m, \beta_m]) & \text{if } v = 0, \\
([\alpha, \beta_1], [\alpha_2, \beta_2], \ldots, [\alpha_m, \beta_m]) & \text{if } v = \varphi, \\
([0, 0], [0, 0], \ldots, [0, 0]) & \text{if } v \in \{\kappa, \ell\}. 
\end{cases}
\]

It is easy to verify that $\widehat{G}$ is an IVmPF subalgebra.

Lemma 3.3. If $\widehat{G}$ is an IVmPF subalgebra of $X$, then $\widehat{G} (0) \geq \widehat{G} (v)$ for all $v \in X$.

Proof. Let $v \in X$. Then, we have
\[
\begin{align*}
\widehat{\mathcal{F}}_i \circ \widehat{G} (0) &= \widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast v) \\
&\geq \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \\
&= \widehat{\mathcal{F}}_i \circ \widehat{G} (v),
\end{align*}
\]
as required.

Theorem 3.4. An IVmPF set $\widehat{G}$ is an IVmPF subalgebra of $X$ if and only if $\widehat{G}^+_i$ and $\widehat{G}^-_i$ are fuzzy subalgebras of $X$ for all $i$.

Proof. ($\Rightarrow$) Assume that $\widehat{G} = ([\widehat{G}^+_1, \widehat{G}^-_1], [\widehat{G}^+_2, \widehat{G}^-_2], \ldots, [\widehat{G}^+_m, \widehat{G}^-_m])$ is an IVmPF subalgebra of $X$. Then for any $v, \kappa \in X$,
\[
\begin{align*}
\widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast \kappa) &\geq \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa) \quad \forall i \in \{1, 2, \ldots, m\},
\end{align*}
\]
implies
\[
\begin{align*}
\left[\widehat{G}^-_i (v \ast \kappa), \widehat{G}^+_i (v \ast \kappa)\right] &\geq \left[\widehat{G}^-_i (v), \widehat{G}^+_i (v)\right] \land \left[\widehat{G}^-_i (\kappa), \widehat{G}^+_i (\kappa)\right] \\
&= \left[\widehat{G}^-_i (v) \land \widehat{G}^-_i (\kappa), \widehat{G}^+_i (v) \land \widehat{G}^+_i (\kappa)\right].
\end{align*}
\]

Therefore, $\widehat{G}^+_i (v \ast \kappa) \geq \widehat{G}^-_i (v) \land \widehat{G}^-_i (\kappa)$ and $\widehat{G}^-_i (v \ast \kappa) \geq \widehat{G}^+_i (v) \land \widehat{G}^+_i (\kappa)$.

Hence, $\widehat{G}$ is an IVmPF subalgebra of $X$. 

Definition 3.5. Let $\widehat{G}$ be any IVmPF set. For $[\alpha, \beta] = ([\alpha_1, \beta_1], [\alpha_2, \beta_2], \ldots, [\alpha_m, \beta_m]) \in S[0,1]^m$ define a level subset $U (\widehat{G}; [\alpha, \beta])$ as follows:
\[
U (\widehat{G}; [\alpha, \beta]) = \{x \in X | \widehat{\mathcal{F}}_i \circ \widehat{G} (x) \geq [\alpha_i, \beta_i] \text{ for all } i \in \{1, 2, \ldots, m\}\}.
\]

Theorem 3.6. An IVmPF set $\widehat{G}$ is an IVmPF subalgebra of $X$ if and only if each nonempty level subset $U (\widehat{G}; [\alpha, \beta])$ is a subalgebra of $X$ for all $[\alpha, \beta] \in S[0,1]^m$.

Proof. ($\Rightarrow$) Take any $v, \kappa \in U (\widehat{G}; [\alpha, \beta])$. Therefore, $\widehat{\mathcal{F}}_i \circ \widehat{G} (v) \geq [\alpha_i, \beta_i]$ and $\widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa) \geq [\alpha_i, \beta_i]$ for all $i \in \{1, 2, \ldots, m\}$. Having $\widehat{G}$ an IVmPF subalgebra of $X$, implies
\[
\begin{align*}
\widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast \kappa) &\geq \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa) \\
&\geq [\alpha_i, \beta_i] \land [\alpha_i, \beta_i] \\
&= [\alpha_i, \beta_i].
\end{align*}
\]

Therefore, $v \ast \kappa \in U (\widehat{G}; [\alpha, \beta])$.

($\Leftarrow$) Assume that $U (\widehat{G}; [\alpha, \beta])$ is a subalgebra of $X$ for all $[\alpha, \beta] \in S[0,1]^m$. On contrary, let $\widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast \kappa) < \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa)$ for some $v, \kappa \in X$. Then, $\exists [\gamma, \lambda] = ([\gamma_1, \lambda_1], [\gamma_2, \lambda_2], \ldots, [\gamma_m, \lambda_m]) \in S[0,1]^m$ such that $\widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast \kappa) < [\gamma_i, \lambda_i] \leq \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa)$ for each $i \in \{1, 2, \ldots, m\}$ implies $v, \kappa \in U (\widehat{G}; [\gamma, \lambda])$ but $v \ast \kappa \notin U (\widehat{G}; [\gamma, \lambda])$, which is a contradiction. Therefore, $\widehat{\mathcal{F}}_i \circ \widehat{G} (v \ast \kappa) \geq \widehat{\mathcal{F}}_i \circ \widehat{G} (v) \land \widehat{\mathcal{F}}_i \circ \widehat{G} (\kappa)$ for all $i \in \{1, 2, \ldots, m\}$ and $v, \kappa \in X$. 

Example 2.

Consider a BCK-algebra in which $X = \{0, \varnothing, \mathcal{F}, \kappa, \ell\}$ and $*$ is defined by the following table:

|   | 0 | \varnothing | \mathcal{F} | \kappa | \ell |
|---|---|-------------|-------------|-------|-----|
| 0 | 0 | 0          | 0          | 0     | 0   |
| \varnothing | 0 | 0          | \varnothing | 0     | 0   |
| \mathcal{F} | \varnothing | \mathcal{F} | \varnothing | \mathcal{F} | \varnothing |
| \kappa | \kappa | \kappa | \kappa | \kappa | \ell |
| \ell | \ell | \ell | \ell | \ell | \ell |

Now define an IVmPF set $\mathcal{G}$ on $X$ as

$$\mathcal{G}(v) = \begin{cases} [0.8, 0.8] = [0.8, 0.8], [0.8, 0.8], ..., [0.8, 0.8] & \text{if } v = 0, \\ [0.4, 0.4] = [0.4, 0.4], [0.4, 0.4], ..., [0.4, 0.4] & \text{if } v = \varnothing, \\ [0.5, 0.5] = [0.5, 0.5], [0.5, 0.5], ..., [0.5, 0.5] & \text{if } v = \mathcal{F}, \\ [0.7, 0.7] = [0.7, 0.7], [0.7, 0.7], ..., [0.7, 0.7] & \text{if } v = \kappa, \\ [0.3, 0.3] = [0.3, 0.3], [0.3, 0.3], ..., [0.3, 0.3] & \text{if } v = \ell. \end{cases}$$

Therefore,

$$U\left(\mathcal{G}; [\alpha, \beta]\right) = \begin{cases} X, & \text{if } [0, 0] < [\alpha, \beta] \leq [0.3, 0.3]; \\ \{0, \varnothing, \kappa\}, & \text{if } [0, 0] < [\alpha, \beta] \leq [0.4, 0.4]; \\ \{0, \kappa\}, & \text{if } [0, 0] < [\alpha, \beta] \leq [0.5, 0.5]; \\ \{0\}, & \text{if } [0, 0] < [\alpha, \beta] \leq [0.8, 0.8]; \\ \varnothing, & \text{if } [0, 0] < [\alpha, \beta] \leq [1, 1]. \end{cases}$$

Since for all $[\alpha, \beta] \in S[0, 1]^m$, $U\left(\mathcal{G}; [\alpha, \beta]\right)$ is a subalgebra of $X$. Therefore by Theorem 3.6, $\mathcal{G}$ is an IVmPF subalgebra.

Example 3.

Consider a BCI-algebra in which $X = \{0, 1, \varnothing, \kappa, \ell\}$ and $*$ is defined by the following table:

|   | 0 | 1 | \varnothing | \kappa | \ell |
|---|---|---|-------------|-------|-----|
| 0 | 0 | 0 | \varnothing | \varnothing | \varnothing |
| 1 | 1 | 0 | \varnothing | \varnothing | \varnothing |
| \varnothing | \varnothing | \varnothing | \varnothing | \varnothing |
| \kappa | \kappa | \kappa | \kappa | \kappa |
| \ell | \ell | \ell | \ell | \ell |

Now define an IVSPF set $\mathcal{G}$ on $X$ as

$$\mathcal{G}(v) = \begin{cases} ([0.6, 0.7], [0.5, 0.8], [0.3, 0.4], [0.7, 0.8], [0.6, 0.7]) & \text{if } v = 0, \\ ([0.5, 0.6], [0.3, 0.5], [0.2, 0.3], [0.5, 0.6], [0.4, 0.6]) & \text{if } v = 1, \\ ([0.2, 0.4], [0.1, 0.2], [0.1, 0.2], [0.2, 0.3], [0.2, 0.3]) & \text{if } v \in \{\varnothing, \ell\}, \\ ([0.3, 0.4], [0.2, 0.3], [0.1, 0.2], [0.3, 0.5], [0.4, 0.5]) & \text{if } v = \kappa. \end{cases}$$

It is routine to verify that $\mathcal{G}$ is an IVSPF ideal.

**Lemma 4.2.** Let $\mathcal{G}$ be an IVmPF ideal of $X$ and $\nu, \kappa \in X$ such that $\nu \leq \kappa$. Then,

$$\mathcal{G}(\nu) \geq \mathcal{G}(\kappa).$$

**Proof.** Let $\nu, \kappa \in X$ such that $\nu \leq \kappa$. Then,

$$\overline{\mathcal{R}} \mathcal{G}(\nu) \geq \overline{\mathcal{R}} \mathcal{G}(\nu \kappa) \wedge \overline{\mathcal{R}} \mathcal{G}(\kappa)$$

$$= \overline{\mathcal{R}} \mathcal{G}(0) \wedge \overline{\mathcal{R}} \mathcal{G}(\kappa)$$

$$= \overline{\mathcal{R}} \mathcal{G}(\kappa).$$

Hence, $\mathcal{G}(\nu) \geq \mathcal{G}(\kappa)$.

**Lemma 4.3.** Let $\mathcal{G}$ be an IVmPF ideal of $X$ and $\nu, \kappa, h \in X$ such that $\nu \kappa \leq h$. Then,

$$\mathcal{G}(\nu) \geq \mathcal{G}(\kappa) \wedge \mathcal{G}(h).$$

**Proof.** Let $\nu, \kappa, h \in X$ such that $\nu \kappa \leq h$. Then by Lemma 4.2, we have

$$\overline{\mathcal{R}} \mathcal{G}(\nu \kappa) \geq \overline{\mathcal{R}} \mathcal{G}(h).$$

As $\mathcal{G}$ is an IVmPF ideal of $X$, so

$$\overline{\mathcal{R}} \mathcal{G}(\nu) \geq \overline{\mathcal{R}} \mathcal{G}(\nu \kappa) \wedge \overline{\mathcal{R}} \mathcal{G}(\kappa)$$

$$\geq \overline{\mathcal{R}} \mathcal{G}(h) \wedge \overline{\mathcal{R}} \mathcal{G}(\kappa).$$

It follows that $\mathcal{G}(\nu) \geq \mathcal{G}(\kappa) \wedge \mathcal{G}(h)$.

**Theorem 4.4.** In a BCK4-algebra $X$, every IVmPF ideal of $X$ is an IVmPF subalgebra.
Proof. Suppose that \( \mathcal{G} \) is any IVmPF ideal and let \( v, \kappa \in X \). As \( v \ast \kappa \leq v \) in \( X \), so by Lemma 4.2, \( \mathcal{R} \circ \mathcal{G} (v) \leq \mathcal{R} \circ \mathcal{G} (v \ast \kappa) \). Since \( \mathcal{G} \) is an IVmPF ideal of \( X \), we have

\[
\mathcal{R} \circ \mathcal{G} (v \ast \kappa) \geq \mathcal{R} \circ \mathcal{G} (v)
\]

\[
\geq \mathcal{R} \circ \mathcal{G} (v) \land \mathcal{R} \circ \mathcal{G} (\kappa)
\]

\[
= \mathcal{R} \circ \mathcal{G} (v) \land \mathcal{R} \circ \mathcal{G} (\kappa)
\]

Hence, \( \mathcal{G} \) is an IVmPF subalgebra.

Remark 1. The converse of Theorem 4.4 is not true in general.

Example 4.

Consider a BCK-algebra in which \( X = \{0, \emptyset, \kappa, \ell\} \) and \( * \) is described by the following table:

| 0 | 0 | 0 | 0 |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 |

Now define an IV3PF set \( \mathcal{G} \) on \( X \) as:

\[
\mathcal{G} (v) = \begin{cases}
(0.7, 0.8), [0.3, 0.5], [0.2, 0.3)] & \text{if } v = 0, \\
(0.5, 0.6), [0.1, 0.3], [0.1, 0.2) & \text{if } v = \emptyset, \\
(0.3, 0.4), [0.1, 0.1], [0.1, 0.11) & \text{if } v = \kappa, \\
(0.6, 0.7), [0.2, 0.4], [0.1, 0.3] & \text{if } v = \ell.
\end{cases}
\]

By routine calculation one can verify that \( \mathcal{G} \) is an IV3PF subalgebra but not an IV3PF ideal because \( [0.5, 0.6] = \mathcal{R} \circ \mathcal{G} (\emptyset) \not\leq \mathcal{R} \circ \mathcal{G} (\emptyset \ast \ell) \land \mathcal{R} \circ \mathcal{G} (\ell) = (0.6, 0.7) \).

The following result provides a condition for an IVmPF subalgebra to be an IVmPF ideal.

Theorem 4.5. Let \( \mathcal{G} \) be an IVmPF subalgebra of \( X \). Then \( \mathcal{G} \) is an IVmPF ideal \( \iff \) for all \( v, \kappa, h \in X \) such that \( v \ast \kappa \leq h \) implies \( \mathcal{G} (v) \geq \mathcal{G} (\kappa) \land \mathcal{G} (h) \).

Proof. \( \Rightarrow \) follows from Lemma 4.3.

\( \Leftarrow \) Let \( \mathcal{G} \) be an IVmPF subalgebra such that for all \( v, \kappa, h \in X \) with \( v \ast \kappa \leq h \) implies \( \mathcal{G} (v) \geq \mathcal{G} (\kappa) \land \mathcal{G} (h) \). As \( v \ast (v \ast \kappa) \leq \kappa \), so by hypothesis

\[
\mathcal{G} (v) \geq \mathcal{G} (v \ast \kappa) \land \mathcal{G} (\kappa).
\]

Hence, \( \mathcal{G} \) is an IVmPF ideal of \( X \).

In the following result, we give a relation between an IVmPF ideal and fuzzy ideals of \( X \).

Theorem 4.6. An IVmPF set \( \mathcal{G} \) is an IVmPF ideal of \( X \) \( \iff \) each nonempty level subset \( \Delta \mathcal{G} : [\alpha, \beta] \) is an ideal of \( X \) \( \forall [\alpha, \beta] = ([0.1], [0.1], ... [a_m, b_m] \in S(0, 1)^m] \).

Proof. \( \Rightarrow \) Assume that \( \mathcal{G} (v) = ([\mathcal{G}_1^- (v), \mathcal{G}_1^+ (v)], ..., [\mathcal{G}_m^- (v), \mathcal{G}_m^+ (v)]) \) in an IVmPF ideal of \( X \) for all \( v \in X \). For any \( v \in X \), we have

\[
\mathcal{R} \circ \mathcal{G} (v) \geq \mathcal{R} \circ \mathcal{G} (\kappa) \forall \mathcal{G} (v) \in [1, 2, ..., m].
\]

It follows that \( \mathcal{G}_1^- (0), \mathcal{G}_1^+ (0) \geq \mathcal{G}_1^- (v), \mathcal{G}_1^+ (v) \).

Hence, \( \mathcal{G} \) is an IVmPF ideal.

The following result provides a correspondence between an IVmPF ideal of \( X \) and an ideal of \( X \).

Theorem 4.7. An IVmPF set \( \mathcal{G} \) is an IVmPF ideal of \( X \) \( \iff \) each nonempty level subset \( \Delta \mathcal{G} : [\alpha, \beta] \) is an ideal of \( X \) \( \forall [\alpha, \beta] = ([0.1], [0.1], ... [a_m, b_m] \in S(0, 1)^m] \).

Proof. \( \Rightarrow \) Let us suppose that \( \mathcal{G} \) is an IVmPF ideal of \( X \) and \( v \in U \mathcal{G} : [\alpha, \beta] \). Then \( \mathcal{R} \circ \mathcal{G} (v) \geq [\alpha, \beta] \). By hypothesis, \( \mathcal{R} \circ \mathcal{G} (0) \geq [\alpha, \beta] \). Thus, \( 0 \in U \mathcal{G} : [\alpha, \beta] \). Next, take any \( v \ast \kappa \in U \mathcal{G} : [\alpha, \beta] \) and \( \kappa \in U \mathcal{G} : [\alpha, \beta] \). Therefore, \( \mathcal{R} \circ \mathcal{G} (v \ast \kappa) \geq [\alpha, \beta] \) and \( \mathcal{R} \circ \mathcal{G} (\kappa) \geq [\alpha, \beta] \). As \( \mathcal{G} \) is an IVmPF ideal, so

\[
\mathcal{R} \circ \mathcal{G} (v) \geq \mathcal{R} \circ \mathcal{G} (\kappa) \land \mathcal{R} \circ \mathcal{G} (\kappa)
\]

\[
= [\alpha, \beta] \land [\alpha, \beta]
\]

It follows that \( v \in U \mathcal{G} : [\alpha, \beta] \). Hence, \( U \mathcal{G} : [\alpha, \beta] \) is an ideal.
(⇐) Now let \( U \left( \mathcal{F} ; [a, \beta] \right) \) be an ideal of \( X \) \( \forall [a, \beta] \in S(0, 1)^m \).

If \( \mathcal{F} \mathcal{O} (v) < \mathcal{F} \mathcal{O} (v) \) for some \( v \in X \) and to \( \exists \mathcal{F} \mathcal{O} (v) \) such that \( \mathcal{F} \mathcal{O} (v) < \mathcal{F} \mathcal{O} (v) \) for all \( v \in \{ 1, 2, \ldots, m \} \) implies \( v \in U \left( \mathcal{F} ; [\delta, \gamma] \right) \)

but \( 0 \notin U \left( \mathcal{F} ; [\delta, \gamma] \right) \), which is a contradiction. Therefore, \( \mathcal{F} \mathcal{O} (v) \) for all \( v \in X \) and \( i \in \{ 1, 2, \ldots, m \} \). Again, if \( \mathcal{F} \mathcal{O} (v) < \mathcal{F} \mathcal{O} (v) \) for some \( v, \kappa \in X \) such that \( \mathcal{F} \mathcal{O} (v) < \mathcal{F} \mathcal{O} (v) \) for all \( i \in \{ 1, 2, \ldots, m \} \) implies \( v \in \mathcal{F} \mathcal{O} (v) \) and \( v \in U \left( \mathcal{F} ; [\delta, \gamma] \right) \)

but \( v \notin U \left( \mathcal{F} ; [\delta, \gamma] \right) \), which is again a contradiction. Therefore, \( \mathcal{F} \mathcal{O} (v) \) for all \( v, \kappa \in X \) and \( i \in \{ 1, 2, \ldots, m \} \).

5. INTERVAL-VALUED m-POLAR COMMUTATIVE IDEALS

The notion of an IVmPF commutative ideal of BCK/BCI-algebras is defined. Relations among the IVmPF subalgebras, IVmPF ideals and IVmPF commutative ideals are discussed.

Definition 5.1. An IVmPF set \( \mathcal{G} \) is called an IVmPF commutative ideal if the following conditions satisfy for all \( v, \kappa, h \in X \):

\[
\begin{align*}
(1) & \quad \mathcal{G} (0) \geq \mathcal{G} (v), \\
(2) & \quad \mathcal{G} (v * (\kappa * (v * h))) \geq \mathcal{G} ((v * \kappa) * h) \wedge \mathcal{G} (h),
\end{align*}
\]

that is,

\[
\begin{align*}
(1) & \quad \mathcal{F} \mathcal{O} (0) \geq \mathcal{F} \mathcal{O} (v), \\
(2) & \quad \mathcal{F} \mathcal{O} (v * (\kappa * (v * h))) \geq \mathcal{F} \mathcal{O} ((v * \kappa) * h) \wedge \mathcal{F} \mathcal{O} (h),
\end{align*}
\]

\( \forall i \in \{ 1, 2, \ldots, m \} \).

Example 5.

Consider the BCK-algebra \( X \) of Example 1. Let \( [\alpha, \varphi] = \left( [\alpha_1, \beta_1] , [\alpha_2, \beta_2] , \ldots , [\alpha_m, \beta_m] \right) \), \( [\alpha, \beta] = \left( [\alpha_1, \beta_1] , [\alpha_2, \beta_2] , \ldots , [\alpha_m, \beta_m] \right) \), \( [\delta, \gamma] = \left( [\delta_1, \gamma_1] , [\delta_2, \gamma_2] , \ldots , [\delta_m, \gamma_m] \right) \) \( \in S(0, 1)^m \) such that \( [\alpha, \varphi] \geq [\alpha, \beta] \geq [\delta, \gamma] \). Now define an IVmPF set \( \mathcal{G} \) on \( X \) as:

\[
\mathcal{G} (v) =
\begin{cases}
[\alpha, \varphi] = \left( [\alpha_1, \beta_1] , [\alpha_2, \beta_2] , \ldots , [\alpha_m, \beta_m] \right) & \text{if } v = 0, \\
[\alpha, \beta] = \left( [\alpha_1, \beta_1] , [\alpha_2, \beta_2] , \ldots , [\alpha_m, \beta_m] \right) & \text{if } v \in \{ \varphi, \kappa \}, \\
[\delta, \gamma] = \left( [\delta_1, \gamma_1] , [\delta_2, \gamma_2] , \ldots , [\delta_m, \gamma_m] \right) & \text{if } v = \ell.
\end{cases}
\]

It is easy to verify that \( \mathcal{G} \) is an IVmPF commutative ideal.

Theorem 5.2. In any BCK-algebra \( X \), every IVmPF commutative ideal of \( X \) is an IVmPF ideal.

Proof. For any IVmPF commutative ideal \( \mathcal{G} \) of \( X \) and \( v, \kappa \in X \), we have

\[
\begin{align*}
\mathcal{G} \mathcal{O} (v) &= \mathcal{G} \mathcal{O} (v * (0 * (0 * v))) \\
&\geq \mathcal{G} \mathcal{O} ((v * 0) * \kappa) \wedge \mathcal{G} \mathcal{O} (\kappa) \\
&= \mathcal{G} \mathcal{O} (v * \kappa) \wedge \mathcal{G} \mathcal{O} (\kappa).
\end{align*}
\]

Hence, \( \mathcal{G} \) is an IVmPF ideal.

Corollary 5.3. Every IVmPF commutative ideal of \( X \) is an IVmPF subalgebra of \( X \).

Remark 2. In general, the converse of Theorem 5.2 is not true as shown next.

Example 6.

Consider a BCK-algebra in which \( X = \{ 0, \varphi, \kappa, \ell \} \) and * is described with the following table:

| * | 0 | \varphi | \kappa | \ell |
|---|---|---------|-------|-----|
| 0 | 0 | 0 | 0 | 0 |
| \varphi | 0 | 0 | 0 | 0 |
| \kappa | \kappa | \kappa | \kappa | 0 |
| \ell | \ell | \ell | \ell | \ell |

Let \( \left[ \theta, \lambda \right] = \left( [\theta_1, \lambda_1] , [\theta_2, \lambda_2] , \ldots , [\theta_m, \lambda_m] \right) \), \( [\psi, \varphi] = \left( [\psi_1, \varphi_1] , [\psi_2, \varphi_2] , \ldots , [\psi_m, \varphi_m] \right) \), \( [\rho, \sigma] = \left( [\rho_1, \sigma_1] , [\rho_2, \sigma_2] , \ldots , [\rho_m, \sigma_m] \right) \) \( \in S(0, 1)^m \) such that \( \left[ \theta, \lambda \right] \geq \left[ \psi, \varphi \right] \geq \left[ \rho, \sigma \right] \). Now define an IVmPF set \( \mathcal{G} \) on \( X \) as:

\[
\mathcal{G} (v) =
\begin{cases}
\left[ \theta, \lambda \right] = \left( [\theta_1, \lambda_1] , [\theta_2, \lambda_2] , \ldots , [\theta_m, \lambda_m] \right) & \text{if } v = 0, \\
\left[ \psi, \varphi \right] = \left( [\psi_1, \varphi_1] , [\psi_2, \varphi_2] , \ldots , [\psi_m, \varphi_m] \right) & \text{if } v = \varphi, \\
\left[ \rho, \sigma \right] = \left( [\rho_1, \sigma_1] , [\rho_2, \sigma_2] , \ldots , [\rho_m, \sigma_m] \right) & \text{if } v \in \{ \kappa, \ell \}.
\end{cases}
\]

It can be shown that \( \mathcal{G} \) is an IVmPF ideal but not an IVmPF commutative ideal because \( \left[ \lambda_1, \sigma_1 \right] = \mathcal{F} \mathcal{O} (\mathcal{F} ) = \mathcal{F} \mathcal{O} (\mathcal{F} ) \). Following two results provide conditions for an IVmPF ideal to be an IVmPF commutative ideal.

Theorem 5.4. Let \( \mathcal{G} \) be an IVmPF ideal of \( X \). Then \( \mathcal{G} \) is an IVmPF commutative ideal if for all \( v, \kappa \in X \),

\[
\mathcal{G} (v * (\kappa * (v * v))) \geq \mathcal{G} ((v * \kappa) * h) \wedge \mathcal{G} (h).
\]

Proof. (⇒) Let \( \mathcal{G} \) be an IVmPF commutative ideal. Then for all \( v, \kappa \in X \), we have

\[
\mathcal{G} (v * (\kappa * (v * v))) \geq \mathcal{G} ((v * \kappa) * h) \wedge \mathcal{G} (h).
\]

Taking \( h = 0 \), we get

\[
\mathcal{G} (v * (\kappa * (v * v))) \geq \mathcal{G} (v * \kappa) \wedge \mathcal{G} (0) = \mathcal{G} (v * \kappa) \wedge \mathcal{G} (0) = \mathcal{G} (v * \kappa).
\]
Let $\mathcal{G}$ be an IVmPF ideal such that $\mathcal{G} ((v \ast (\kappa \ast (\kappa \ast v)))) \geq \mathcal{G} ((v \ast \kappa))$ for all $v, \kappa \in X$. By assumption, we have for all $v, \kappa, h \in X$

$$\mathcal{G} (v \ast \kappa) \geq \mathcal{G} ((v \ast \kappa) \ast h) \land \mathcal{G} (h).$$

Therefore, $\mathcal{G} ((v \ast (\kappa \ast (\kappa \ast v)))) \geq \mathcal{G} ((v \ast \kappa) \ast h) \land \mathcal{G} (h)$, as required.

**Theorem 5.5.** Let $X$ be a commutative BCK-algebra. Then every IVmPF ideal of $X$ is an IVmPF commutative ideal.

**Proof.** Suppose that $\mathcal{G}$ is an IVmPF ideal of $X$. Then for all $v, \kappa, h \in X$,

$$((v \ast (\kappa \ast (\kappa \ast v))) \ast ((v \ast \kappa) \ast h)) \ast h \leq (v \ast (\kappa \ast (\kappa \ast v))) \ast (v \ast \kappa) \ast ((v \ast \kappa) \ast h) \leq (v \ast (\kappa \ast (\kappa \ast v))) \ast (v \ast \kappa) = (v \ast (v \ast \kappa)) \ast (\kappa \ast (\kappa \ast v)) = 0$$

It follows that $((v \ast (\kappa \ast (\kappa \ast v))) \ast ((v \ast \kappa) \ast h)) \leq h$. As $\mathcal{G}$ is an IVmPF ideal of $X$, then by Lemma 4.3, $\mathcal{G} ((v \ast (\kappa \ast (\kappa \ast v)))) \geq \mathcal{G} ((v \ast \kappa) \ast h) \land \mathcal{G} (h)$.

### 6. CONCLUSION

In this paper, by applying the theory of IVmPF on BCK/BCI-algebra, the notions of interval-valued $m$-polar fuzzy subalgebras, interval-valued $m$-polar fuzzy ideals and interval-valued $m$-polar fuzzy commutative ideals are introduced and some essential properties are discussed. Characterizations of interval-valued $m$-polar fuzzy subalgebras and interval-valued $m$-polar fuzzy ideals are considered. Moreover, the relations among interval-valued $m$-polar fuzzy subalgebras, interval-valued $m$-polar fuzzy ideals and interval-valued $m$-polar fuzzy commutative ideals are obtained. This work can be a basis for further analysis of the interval-valued $m$-polar fuzzy structures in related algebraic structures. For future study, this concept may be applied to study some application fields like decision-making, knowledge base system, data analysis, and so on. In our opinion, these definitions and main results can be similarly extended to some other algebraic systems such as subtraction algebras, B-algebras, MV-algebras, d-algebras, Q-algebras, and so on.

### CONFLICTS OF INTEREST

Authors declare that they have no conflicts of interest.

### AUTHORS’ CONTRIBUTIONS

All authors have contributed to the manuscript equally.

### ACKNOWLEDGMENTS

The authors are grateful to the anonymous referee(s) for a careful checking of the details and for helpful comments that improved this paper. This work was supported by the Taif University Researchers Supporting Project (TURSP-2020/246), Taif University, Taif, Saudi Arabia.

### REFERENCES

[1] Y.B. Jun, K.J. Lee, J. Zhan, Soft $p$-ideals of soft $BCI$-algebras, Comput. Math. Appl. 58 (2009), 2060–2068.

[2] Y.B. Jun, C.H. Park, Applications of soft sets in ideal theory of BCK/BCI-algebras, Inform. Sci. 178 (2008), 2466–2475.

[3] Y.L. Liu, X.H. Zhang, Z.C. Yue, $q$-ideals and $a$-ideals in $BCI$-algebras, SEA Bull. Math. 24 (2000), 243–253.

[4] J. Meng, On ideals in $BCI$-algebras, Math. Japon. 40 (1994), 143–154.

[5] G. Muhiuddin, A.M. Al-roqi, Cubic soft sets with applications in BCK/BCI-algebras, Ann. Fuzzy Math. Inform. 8 (2014), 291–304.

[6] G. Muhiuddin, A.M. Al-roqi, S. Aldhafeeri, Filter theory in MTL-algebras based on Uni-soft property, Bull. Iranian Math. Soc. 43 (2017), 2293–2306.

[7] G. Muhiuddin, A.M. Al-roqi, Unisoft filters in $R0$-algebras, J. Comput. Anal. Appl. 19 (2015), 133–143. http://www.eudoxuspress.com/neweudoxusvolumeshtcs.html

[8] T. Senapati, Y.B. Jun, G. Muhiuddin, K.P. Shum, Cubic intuition-istic structures applied to ideals of BCI-algebras, Analele Stintifice Univ. Ovidius Constanta-Ser. Mat. 27 (2019), 213–232.

[9] L.A. Zadeh, Fuzzy sets, Inf. Control. 8 (1965), 338–353.

[10] R. Biswas, Rosenfelds fuzzy subgroups with interval-valued membership function, Fuzzy Sets Syst. 63 (1994), 87–90.

[11] Y.B. Jun, Interval-valued fuzzy subalgebras/ideals in BCK-algebras, Sci. Math. 3 (2000), 433–444. http://www.jams.or.jp/scm/contents/Vol-3-3/3-3-17.pdf.

[12] T. Bej, M. Pal, Interval-valued doubt fuzzy ideals in BCK-algebras, Int. J. Fuzzy Syst. Appl. 8 (2019), 101–121.

[13] X. Ma, J. Zhan, Y.B. Jun, Some types of $(e, e \in q)$-interval valued fuzzy ideals BCI-algebras, Iranian J. Fuzzy Syst. 6 (2009), 53–63. https://ijfs.usb.ac.ir/article_200_da5a23de010339b6dc1ec0f1cf5965c.pdf.

[14] X. Ma, J. Zhan, B. Davvaz, Y.B. Jun, Some kinds of $(e, e \in q)$-interval valued fuzzy ideals of BCI-algebras, Inform. Sci. 178 (2008), 3738–3754.

[15] K.J. Lee, Bi-polar fuzzy subalgebras and bi-polar fuzzy ideals of BCK/BCI-algebras, Bull. Malaysian Math. Sci. Soc. 32 (2009), 361–373. https://www.emis.de/journals/BMMSS/pdf/acceptedpapers/2008-07-16.pdf.

[16] M. Ibrar, A. Khan, B. Davvaz, Characterizations of regular ordered semi-groups in terms of $(\alpha, \beta)$-bipolar fuzzy generalized bi-ideals, Int. J. Fuzzy Syst. 33 (2017), 365–376.

[17] S. Bashir, M. Fatima, M. Shabir, Regular ordered ternary semigroups in terms of bipolar fuzzy ideals, Mathematics. 7 (2019), 233.

[18] D. Al-Kadi, G. Muhiuddin, Bipolar fuzzy BCI-implicative ideals of BCI-algebras, Ann. Commun. Math. 3 (2020), 88–96. http://www.technoskypub.com/wp-content/uploads/2020/06/9-v3-1-km-bipolar-fuzzy-bci-implicative-ideas.pdf.

[19] G. Muhiuddin, M.M. Takallo, R.A. Borzooei, Y.B. Jun, m-polar fuzzy q-ideals in BCI-algebras, J. King Saud Univ. Sci. 32 (2020), 2803–2809.
[20] G. Muhiuddin, B. Jun, Bipolar-valued fuzzy soft hyper BCK ideals in hyper BCK algebras, Discrete Math. Algorithms Appl. 12 (2020), 1–16.

[21] G. Muhiuddin, D. Al-Kadi, A. Mehboob, K.P. Shum, New types of bipolar fuzzy ideals of BCK-algebras, Int. J. Anal. Appl. 18 (2020), 859–875.

[22] G. Muhiuddin, Bipolar fuzzy KU-subalgebras/ideals of KU-algebras, Ann. Fuzzy Math. Inform. 8 (2014), 409–418. http://www.afmi.or.kr/.

[23] J. Chen, S. Li, S. Ma, X. Wang, m-polar fuzzy sets: an extension of bipolar fuzzy sets, Sci. World J. 2014 (2014), 416530.

[24] M. Akram, N. Waseem, P. Liu, Novel approach in decision making with m-polar fuzzy ELECTRE-I, Int. J. Fuzzy Syst. 21 (2019), 1117–1129.

[25] M. Akram, A. Farooq, K.P. Shum, On m-polar fuzzy Lie subalgebras, Ital. J. Pure Appl. Math. 36 (2016), 445–454. https://ijpam.uniud.it/online_issue/201636/38-AkramFarookShum.pdf.

[26] M. Akram, A. Farooq, m-polar fuzzy Lie ideals of Lie algebras, Quasi-Groups Relat. Syst. 24 (2016), 141–150. http://www.quasigroups.eu/.

[27] A. Farooq, G. Alia, M. Akram, m-polar fuzzy groups, Int. J. Algebr. Stat. 5 (2016), 115–127.

[28] M. Sarwar, M. Akram, New applications of m-polar fuzzy matroids, Symmetry. 9 (2017), 319.

[29] S. Mandal, S. Sahoo, G. Ghori, M. Pal, Genus value of m-polar fuzzy graphs, J. Intell. Fuzzy Syst. 34 (2018), 1947–1957.

[30] M. Akram, A. Adeel, m-polar fuzzy graphs and m-polar fuzzy line graphs, J. Discrete Math. Sci. Cryptogr. 20 (2017), 1597–1617.

[31] M. Akram, G. Shahzadi, Certain characterization of m-polar fuzzy graphs by level graphs, Punjab Univ. J. Math. 49 (2017), 1–12. http://pu.edu.pk/images/journal/math/PDF/Paper-1_49_1_17.pdf.

[32] M. Akram, m-Polar Fuzzy Graphs, Studies in Fuzziness and Soft Computing, vol. 371, Springer, Basel, Switzerland, 2019.