Abstract: The principles of convexity and symmetry are inextricably linked. Because of the considerable association that has emerged between the two in recent years, we may apply what we learn from one to the other. In this paper, our aim is to establish the relation between integral inequalities and interval-valued functions (IV-Fs) based upon the pseudo-order relation. Firstly, we discuss the properties of left and right preinvex interval-valued functions (left and right preinvex IV-Fs). Then, we obtain Hermite–Hadamard (HH) and Hermite–Hadamard–Fejér (HH–Fejér) type inequality and some related integral inequalities with the support of left and right preinvex integral inequalities via pseudo-order relation and interval Riemann integral. Moreover, some exceptional special cases are also discussed. Some useful examples are also given to prove the validity of our main results.

Keywords: left and right preinvex interval-valued function; interval Riemann integral; Hermite–Hadamard type inequality; Hermite–Hadamard–Fejér type inequality

1. Introduction

Hanson [1] defined the class of invex functions as one of the most significant extensions of convex functions. Weir and Mond [2], in 1988, used the notion of preinvex functions to demonstrate adequate optimality criteria and duality in nonlinear programming. For a differentiable mapping, the concept of fractional integral identities involving Riemann–Liouville fractional and Hadamard fractional integrals integrals was considered by Wang et al. [3], who identified some inequalities using standard convex, r-convex, m-convex, S-convex, (s, m)-convex, and (β, m)-convex. Moreover, Işcan [4] also used fractional integrals for preinvex functions to obtain various HH–Fejér type inequalities. See [5–8] for other generalizations of the HH–Fejér inequality.

For accurate solutions to various problems in practical mathematics, Moore [9] used interval arithmetic, IV-Fs, and integrals of IV-Fs to establish arbitrarily sharp upper and lower limits. Moore [9] showed that, if a real-valued mapping \( Y(x) \) meets an ordinary Lipschitz condition in \( Y, |Y(x) - Y(\omega)| \leq L|x - \omega| \), for \( \omega, x \in y \), then, the united extension is a Lipschitz interval extension in \( Y \). To combine the study of discrete and continuous dynamical systems, Hilger [10] introduced a time scales theory. The widespread use of dynamic equations and integral inequalities on time scales, in domains as diverse as electrical engineering, quantum physics, heat transfer, neural networks, combinatorics, and population dynamics [11], has highlighted the need for this theory. Young’s inequality,
Minkowski’s inequality, Jensen’s inequality, Hölder’s inequality, **H-H** inequality, Steffensen’s inequality, Opial type inequality and Chebychev’s inequality were all explored by Agarwal et al. [11]. Srivastava et al. [12] discovered some generic time scale weighted Opial type inequalities in 2010. Srivastava et al. [13] also proposed several time-based expansions and generalizations of Maroni’s inequality. Under certain proper conditions, some new local fractional integral analogue of Anderson’s inequality on fractal space was introduced by Wei et al. [14], demonstrating that for classical Anderson’s inequality, it was a novel extension on fractal space. Tunç et al. [15] also constructed an identity for local fractional integrals and derived numerous modifications of the well-known Steffensen’s inequality for fractional integrals. The papers [11,16] and the references therein might be consulted for further information. Bhurjee and Panda [17] identified the parametric form of an IV-F and devised a technique to investigate the existence of a generic interval optimization issue solution. Using the notion of the generalized Hukuhara difference, Lupulescu [18] developed differentiability and integrability for IV-Fs on time scales. Cano et al. [19] developed a novel form of the Ostrowski inequality for gH differentiable IV-Fs in 2015 and achieved an extension of the class of real functions that are not always differentiable. For gH-differentiable IV-Fs, Cano et al. [19] found error limitations to quadrature rules. In addition, Roy and Panda [20] developed the idea of the -monotonic property of IV-Fs in the higher dimension and used extended Hukuhara differentiability to obtain various conclusions. We refer to [21–25], and the references therein, for further information on IV-Fs. An et al. [26] and Zhao et al. [27] recently proposed an (h1, h2)-convex IV-F and harmonically h-convex IV-F, respectively. Moreover, they found certain interval **H-H** type inequalities. Budak et al. [28] also created the **H-H** inequality for a convex IV-F and its product. For more information related to generalized convex functions and fractional inequalities in interval-valued settings, see [29–53] and the references therein.

Inspired by the ongoing research, we introduce the concept of left and right preinvex IV-F and establish the **H-H** and **H-H**-Fejér inequality for left and right preinvex IV-Fs and the product of two left and right preinvex IV-Fs using Riemann integrals in interval-valued settings, which are motivated by the above studies and ideas. We also provide some examples to support our ideas.

2. Preliminaries

First, we offer some background information on interval-valued functions, the theory of convexity, interval-valued integration, and interval-valued fractional integration, which will be utilized throughout the article.

We offer some fundamental arithmetic regarding interval analysis in this paragraph, which will be quite useful throughout the article.

$$Z = [Z_\downarrow, Z_\uparrow], \quad Q = [Q_\downarrow, Q_\uparrow] \quad (Z_\downarrow \leq x \leq Z_\uparrow \text{ and } Q_\downarrow \leq z \leq Q_\uparrow, z \in \mathbb{R})$$

$$Z + Q = [Z_\downarrow, Z_\uparrow] + [Q_\downarrow, Q_\uparrow] = [Z_\downarrow + Q_\downarrow, Z_\uparrow + Q_\uparrow],$$

$$Z - Q = [Z_\downarrow, Z_\uparrow] - [Q_\downarrow, Q_\uparrow] = [Z_\downarrow - Q_\downarrow, Z_\uparrow - Q_\uparrow],$$

$$\min \mathcal{X} = \min\{Z_\downarrow Q_\downarrow, Z_\downarrow Q_\uparrow, Z_\uparrow Q_\downarrow, Z_\uparrow Q_\uparrow\}, \quad \max \mathcal{X} = \max\{Z_\downarrow Q_\downarrow, Z_\downarrow Q_\uparrow, Z_\uparrow Q_\downarrow, Z_\uparrow Q_\uparrow\}$$

$$v(Z_\downarrow, Z_\uparrow) = \begin{cases} [vZ_\downarrow, vZ_\uparrow] & \text{if } v > 0, \\ \{0\} & \text{if } v = 0, \\ [vZ_\downarrow, vZ_\uparrow] & \text{if } v < 0. \end{cases}$$

Let $\mathcal{K}_C, \mathcal{K}_C^+, \mathcal{K}_C^-$ be the set of all closed intervals of $\mathbb{R}$, the set of all closed positive intervals of $\mathbb{R}$ and the set of all closed negative intervals of $\mathbb{R}$. Then, $\mathcal{K}_C, \mathcal{K}_C^+$, and $\mathcal{K}_C^-$ are defined as

$$\mathcal{K}_C = \{[Z_\downarrow, Z_\uparrow] : Z_\downarrow, Z_\uparrow \in \mathbb{R} \text{ and } Z_\downarrow \leq Z_\uparrow\}$$

$$\mathcal{K}_C^+ = \{[Z_\downarrow, Z_\uparrow] : Z_\downarrow, Z_\uparrow \in \mathcal{K}_C \text{ and } Z_\downarrow > 0\}$$

$$\mathcal{K}_C^- = \{[Z_\downarrow, Z_\uparrow] : Z_\downarrow, Z_\uparrow \in \mathcal{K}_C \text{ and } Z_\downarrow < 0\}$$

For $[Z_\downarrow, Z_\uparrow], [Q_\downarrow, Q_\uparrow] \in \mathcal{K}_C$, the inclusion "$\subseteq$" is defined by $[Z_\downarrow, Z_\uparrow] \subseteq [Q_\downarrow, Q_\uparrow]$, if and only if, $Q_\downarrow \leq Z_\downarrow, Z_\uparrow \leq Q_\uparrow$. 
Theorem 1. [9] If \( Y \) is Riemann integrable over \( K \), then, \( Y \) is left and right preinvex iff for all \( Q, Q' \), \( \{ Q, Q' \}, [Z, Z'] \in K_C \), \( Z, Z' \) \( \in K_C \), is a pseudo-order relation.

Remark 2. The left and right preinvex IV-Fs have some very nice properties similar to left and right preinvex functions.

Definition 3. [7] A set \( A \) is said to be convex on \( K \), if \( \omega + \frac{1}{2} \kappa, \omega \in A \) or \( t \omega + (1-t) \kappa \in A \), where \( \kappa : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n \).

Definition 4. [6] Let \( A \) be an invex set. Then, IV-F \( Y : A \to K_C^+ \) is said to be left and right preinvex on \( A \) with respect to \( \zeta \) if

\[
Y(\omega + (1-t)\zeta(\kappa, \omega)) \leq_p tY(\omega) + (1-t)Y(\zeta),
\]

for all \( \omega, \kappa \in A, t \in [0, 1] \), where \( \zeta : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n \). Y is called left and right preinvex on \( A \) with respect to \( \zeta \) if inequality (4) is reversed. Y is called affine if Y is both convex and concave.

Remark 2. The left and right preinvex IV-Fs have some very nice properties similar to left and right convex IV-F:
- if \( Y \) is left and right preinvex IV-F, then, \( \theta Y \) is also left and right preinvex for \( \theta \geq 0 \).
- if \( Y \) and \( \mathcal{D} \) both are left and right preinvex IV-Fs, then, \( \max(Y(\omega), \mathcal{D}(\omega)) \) is also left and right preinvex IV-Fs.

In the case of \( \zeta(\kappa, \omega) = -\omega \), we obtain (4) from (3).

The following outcome is very important in the field of interval-valued calculus because, by using this result, we can easily handle IV-Fs. Basically, Theorem 2 establishes the relation between IV-F \( Y(\omega) \) and lower function \( Y_s(\omega) \) and upper function \( Y^*(\omega) \).

The following assumption will be required to prove the next result regarding the bifunction \( \zeta : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n \), which is known as:
Condition C. [7] Let A be an invex set with respect to ω. For any x, ω ∈ A and t ∈ [0, 1],

\[
\begin{align*}
\zeta(x, \omega + t\zeta(x, \omega)) &= -t\zeta(x, \omega), \\
\zeta(x, \omega + t\zeta(x, \omega)) &= (1-t)\zeta(x, \omega).
\end{align*}
\]

Clearly for t = 0, we have \(\zeta(x, \omega) = 0\) if and only if, \(x = \omega\), for all \(x, \omega \in A\). For the applications of Condition C, see [26,30,34,35].

Theorem 2. [6] Let A be an invex set and \(Y : A \rightarrow K_C^+\) be a IV-F such that

\[
Y(\omega) = [Y_\ast(\omega), Y^\ast(\omega)], \quad \forall \omega \in A.
\]

for all \(\omega \in A\). Then, Y is left and right preinvex IV-F on A, if and only if, \(Y_\ast(\omega)\) and \(Y^\ast(\omega)\) both are preinvex functions.

Remark 3. If \(Y_\ast(\omega) = Y^\ast(\omega)\), then, from (4), one can acquire the following inequality, see [2]:

\[
Y(\omega + (1-t)\zeta(x, \omega)) \leq tY(\omega) + (1-t)Y(x),
\]

for all \(\omega, \in A, t \in [0, 1]\), where \(\zeta : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^n\).

If \(Y_\ast(\omega) = Y^\ast(\omega)\) with \(\zeta(x, \omega) = x - \omega\), then, from (4), one can acquire the following inequality:

\[
Y(t\omega + (1-t)x) \leq tY(\omega) + (1-t)Y(x),
\]

for all \(\omega, x \in K, t \in [0, 1]\).

Example 1. We consider the IV-F \(Y : [0, 1] \rightarrow K_C^+\) defined by \(Y(\omega) = [2, 4]^{\omega^2}\). Since end point functions \(Y_\ast(\omega), Y^\ast(\omega)\) are preinvex functions with respect to \(\zeta(x, \omega) = x - \omega\). Hence, \(Y(\omega)\) is left and right preinvex IV-F.

3. Main Results

In this section, we derive interval \(\mathfrak{K}-\mathfrak{H}\)-type inequalities for left and right preinvex functions in interval-valued settings. Moreover, we provide some nontrivial examples to verify the validity of the theory developed in this study.

Theorem 3. Let \(Y : [v, v + \zeta(\mu, v)] \rightarrow K_C^+\) be a left and right preinvex IV-F such that \(Y(\omega) = [Y_\ast(\omega), Y^\ast(\omega)]\) for all \(\omega \in [v, v + \zeta(\mu, v)]\). If \(Y \in \mathfrak{SR}_{[v, v + \zeta(\mu, v)]}\), then

\[
Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq p \frac{1}{\zeta(\mu, v)} \frac{1}{v} (\text{IR}) \int_{v}^{v + \zeta(\mu, v)} Y(\omega) d\omega \leq p \frac{Y(v + (1-t)\zeta(\mu, v))}{2} \leq p \frac{Y(v) + Y(\mu)}{2} \leq p \frac{Y(v) + Y(\mu)}{2}.
\]

If \(Y\) is left and right preinvex, then, we achieve the following coming inequality:

\[
Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \geq p \frac{1}{\zeta(\mu, v)} \frac{1}{v} (\text{IR}) \int_{v}^{v + \zeta(\mu, v)} Y(\omega) d\omega \geq p \frac{Y(v + (1-t)\zeta(\mu, v))}{2} \leq p \frac{Y(v) + Y(\mu)}{2} \leq p \frac{Y(v) + Y(\mu)}{2}.
\]

Proof. Let \(Y : [v, v + \zeta(\mu, v)] \rightarrow K_C^+\) be a left and right preinvex IV-F. Then, by hypothesis, we have

\[
2Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq p \left[ Y(v + (1-t)\zeta(\mu, v)) + Y(v + t\zeta(\mu, v)) \right].
\]

Therefore, we have

\[
2Y_\ast\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq Y_\ast\left[ (v + (1-t)\zeta(\mu, v)) + (v + t\zeta(\mu, v)) \right],
\]

\[
2Y^\ast\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq Y^\ast\left[ (v + (1-t)\zeta(\mu, v)) + (v + t\zeta(\mu, v)) \right].
\]
Then
\[\begin{align*}
2 \int_0^1 Y_s\left(2v + \frac{\zeta(\mu, v)}{2}\right) dt &\leq \int_0^1 Y_s(v + (1 - t)\zeta(\mu, v)) dt + \int_0^1 Y_s(v + t\zeta(\mu, v)) dt, \\
2 \int_0^1 Y^*\left(2v + \frac{\zeta(\mu, v)}{2}\right) dt &\leq \int_0^1 Y^*(v + (1 - t)\zeta(\mu, v)) dt + \int_0^1 Y^*(v + t\zeta(\mu, v)) dt.
\end{align*}\]

It follows that
\[Y_s\left(2v + \frac{\zeta(\mu, v)}{2}\right) \leq \frac{1}{\zeta(\mu, v)} \int_0^v Y_s(\omega) d\omega,
\]
\[Y^*\left(2v + \frac{\zeta(\mu, v)}{2}\right) \leq \frac{1}{\zeta(\mu, v)} \int_0^v Y^*(\omega) d\omega.
\]

That is
\[\left[ Y_s\left(\frac{2v + \zeta(\mu, v)}{2}\right), Y^*\left(\frac{2v + \zeta(\mu, v)}{2}\right) \right] \leq \frac{1}{p \zeta(\mu, v)} \left[ \int_0^v Y_s(\omega) d\omega, \int_0^v Y^*(\omega) d\omega \right].
\]

Thus,
\[Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq p \frac{1}{\zeta(\mu, v)} \left( IR \int_0^v Y(\omega) d\omega \right) \leq \frac{Y(v) + Y(\mu)}{2}.
\]

Combining (10) and (11), we have
\[Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq p \frac{1}{\zeta(\mu, v)} \left( IR \int_0^v Y(\omega) d\omega \right) \leq \frac{Y(v) + Y(\mu)}{2}.
\]

This completes the proof. \(\square\)

**Remark 4.** If \(\zeta(\mu, v) = \mu - v\), then Theorem 3 reduces to the result for left and right convex IV-F, see [29]:
\[Y\left(\frac{v + \mu}{2}\right) \leq p \frac{1}{\mu - v} \left( IR \int_0^v Y(\omega) d\omega \right) \leq \frac{Y(v) + Y(\mu)}{2}.
\]

If \(Y_s(\omega) = Y^*(\omega)\), then Theorem 3 reduces to the result for the preinvex function, see [30]:
\[Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq \frac{1}{\zeta(\mu, v)} \left( IR \int_0^v Y(\omega) d\omega \right) \leq \frac{[Y(v) + Y(\mu)]}{1} \int_0^1 t dt.
\]

If \(Y_s(\omega) = Y^*(\omega)\) with \(\zeta(\mu, v) = \mu - v\), then Theorem 3 reduces to the result for the convex function, see [31,32]:
\[Y\left(\frac{v + \mu}{2}\right) \leq \frac{1}{\mu - v} \left( IR \int_0^v Y(\omega) d\omega \right) \leq \frac{Y(v) + Y(\mu)}{2}.
\]

**Example 2.** We consider the IV-F \(Y : [v, v + \zeta(\mu, v)] = [0, \zeta(2, 0)] \rightarrow C^+_2\) defined by \(Y(\omega) = [2\omega^2, 4\omega^2]\). Since end point functions \(Y_s(\omega) = 2\omega^2\), \(Y^*(\omega) = 4\omega^2\) are preinvex functions with respect to \(\zeta(\mu, v) = \mu - v\). Hence, \(Y(\omega)\) is left and right preinvex IV-F with respect to \(\zeta(\mu, v) = \mu - v\). We now compute the following
\[Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq p \frac{1}{\zeta(\mu, v)} \left( IR \int_0^v Y(\omega) d\omega \right) \leq \frac{Y(v) + Y(\mu)}{2}.
\]

- \(Y_s\left(\frac{2v + \zeta(\mu, v)}{2}\right) = Y_s(1) = 1,\)
- \(\int_0^v Y(\omega) d\omega = \frac{1}{2} \int_0^2 2\omega^2 d\omega = \frac{8}{3},\)
- \(\frac{Y(v) + Y(\mu)}{2} = 4,\)
that means
\[ 2 \leq \frac{8}{3} \leq 4. \]
Similarly, it can be easily shown that
\[ \displaystyle Y^* \left( \frac{2\nu + \zeta(\mu, \nu)}{2} \right) \leq \frac{1}{\zeta(\mu, \nu)} \int_{\nu}^{\nu + \zeta(\mu, \nu)} Y^*(\omega) d\omega \leq \frac{Y^*(\nu) + Y^*(\mu)}{2} \]
such that
\[ \frac{1}{\zeta(\mu, \nu)} \int_{\nu}^{\nu + \zeta(\mu, \nu)} Y^*(\omega) d\omega = \frac{1}{2} \int_{0}^{2} 4\omega^2 d\omega = \frac{16}{3}, \]
From which, it follows that
\[ 4 \leq \frac{16}{3} \leq 8, \]
that is
\[ [2, 4] \leq p \left[ \frac{8}{3}, \frac{16}{3} \right] \leq p [4, 8] \]
hence,
\[ Y \left( \frac{2\nu + \zeta(\mu, \nu)}{2} \right) \leq p \frac{1}{\zeta(\mu, \nu)} (IR) \int_{\nu}^{\nu + \zeta(\mu, \nu)} Y(\omega) d\omega \leq p \frac{Y(\nu) + Y(\mu)}{2}. \]

**Theorem 4.** Let \( Y, \mathcal{D} : [v, v + \zeta(\mu, \nu)] \to K_C^+ \) be two left and right preinvex IV-F such that \( Y(\omega) = [Y_1(\omega), Y^*(\omega)] \) and \( \mathcal{D}(\omega) = [\mathcal{D}_1(\omega), \mathcal{D}^*(\omega)] \) for all \( \omega \in [v, v + \zeta(\mu, \nu)] \). If \( Y, \mathcal{D} \)
and \( Y \times \mathcal{D} \in \mathcal{IR}_{([v, v + \zeta(\mu, v)])} \), then
\[ \frac{1}{\zeta(\mu, \nu)} (IR) \int_{v}^{v + \zeta(\mu, \nu)} Y(\omega) \times \mathcal{D}(\omega) d\omega \leq p \frac{A(v, \mu) + C(v, \mu)}{3}, \]
where \( A(v, \mu) = Y(v) \times \mathcal{D}(v) + Y(\mu) \times \mathcal{D}(\mu), C(v, \mu) = Y(v) \times \mathcal{D}(\mu) + Y(\mu) \times \mathcal{D}(v), \) and
\( \mathcal{A}(v, \mu) = [\mathcal{A}_1((v, \mu)), \mathcal{A}^*((v, \mu))] \) and \( \mathcal{C}(v, \mu) = [\mathcal{C}_1((v, \mu)), \mathcal{C}^*((v, \mu))] \).

**Proof.** Since \( Y, \mathcal{D} \in \mathcal{IR}_{([v, v + \zeta(\mu, \nu)])} \), then we have
\[ Y_1(v + (1-t)\zeta(\mu, \nu)) \leq tY_1(v) + (1-t)Y_1(\mu), \]
\[ Y^*(v + (1-t)\zeta(\mu, \nu)) \leq tY^*(v) + (1-t)Y^*(\mu). \]
And
\[ \mathcal{D}_1(v + (1-t)\zeta(\mu, \nu)) \leq t\mathcal{D}_1(v) + (1-t)\mathcal{D}_1(\mu), \]
\[ \mathcal{D}^*(v + (1-t)\zeta(\mu, \nu)) \leq t\mathcal{D}^*(v) + (1-t)\mathcal{D}^*(\mu). \]
From the definition of left and right preinvex IV-F, it follows that \( 0 \leq p \ Y(\omega) \) and \( 0 \leq p \ \mathcal{D}(\omega) \), so
\[ Y_1(v + (1-t)\zeta(\mu, \nu)) \times \mathcal{D}_1(v + (1-t)\zeta(\mu, \nu)) \]
\[ \leq ( tY_1(v) + (1-t)Y_1(\mu) ) ( t\mathcal{D}_1(v) + (1-t)\mathcal{D}_1(\mu) ) \]
\[ = Y_1(v) \times \mathcal{D}_1(v) t^2 + Y_1(\mu) \times \mathcal{D}_1(\mu) t^2 + Y_1(v) \times \mathcal{D}_1(\mu) (1-t) + Y_1(\mu) \times \mathcal{D}_1(v) (1-t), \]
\[ Y^*(v + (1-t)\zeta(\mu, \nu)) \times \mathcal{D}^*(v + (1-t)\zeta(\mu, \nu)) \]
\[ \leq ( tY^*(v) + (1-t)Y^*(\mu) ) ( t\mathcal{D}^*(v) + (1-t)\mathcal{D}^*(\mu) ) \]
\[ = Y^*(v) \times \mathcal{D}^*(v) t^2 + Y^*(\mu) \times \mathcal{D}^*(\mu) t^2 + Y^*(v) \times \mathcal{D}^*(\mu) (1-t) + Y^*(\mu) \times \mathcal{D}^*(v) (1-t), \]
Integrating both sides of the above inequality over \([0,1]\), we obtain

\[
\int_0^1 Y_s(v + (1-t)\zeta(\mu, v)) \mathcal{D}_s(v + (1-t)\zeta(\mu, v))
= \frac{1}{\zeta(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y_s(\omega) \mathcal{D}_s(\omega) d\omega
\leq (Y_s(v) \mathcal{D}_s(v) + Y_s(\mu) \mathcal{D}_s(\mu)) \int_0^1 \zeta^2 dt
+ (Y_s(\mu) \mathcal{D}_s(\mu) + Y_s(v) \mathcal{D}_s(v)) \int_0^1 t(1-t) dt,
\]

\[
\int_0^1 Y^*(v + (1-t)\zeta(\mu, v)) \mathcal{D}^*(v + (1-t)\zeta(\mu, v))
= \frac{1}{\zeta(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y^*(\omega) \mathcal{D}^*(\omega) d\omega
\leq (Y^*(v) \mathcal{D}^*(v) + Y^*(\mu) \mathcal{D}^*(\mu)) \int_0^1 \zeta^2 dt
+ (Y^*(\mu) \mathcal{D}^*(\mu) + Y^*(v) \mathcal{D}^*(v)) \int_0^1 t(1-t) dt.
\]

It follows that,

\[
\frac{1}{\zeta(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y_s(\omega) \mathcal{D}_s(\omega) d\omega
\leq A_s((v, \mu)) \int_0^1 \zeta^2 dt + C_s((v, \mu)) \int_0^1 t(1-t) dt,
\]

\[
\frac{1}{\zeta(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y^*(\omega) \mathcal{D}^*(\omega) d\omega
\leq A^*((v, \mu)) \int_0^1 \zeta^2 dt + C^*((v, \mu)) \int_0^1 t(1-t) dt,
\]

that is

\[
\frac{1}{\zeta(\mu, v)} \left[ \int_v^{v+\zeta(\mu, v)} Y_s(\omega) \mathcal{D}_s(\omega) d\omega, \int_v^{v+\zeta(\mu, v)} Y^*(\omega) \mathcal{D}^*(\omega) d\omega \right] \leq \frac{1}{3} \left[ A_s((v, \mu), A^*((v, \mu))) + \left[ \frac{C_s((v, \mu))}{6}, \frac{C^*((v, \mu))}{6} \right] \right].
\]

Thus,

\[
\frac{1}{\zeta(\mu, v)} (IR) \int_v^{v+\zeta(\mu, v)} Y(\omega) \mathcal{D}(\omega) d\omega \leq \frac{1}{3} A(v, \mu) + \frac{C(v, \mu)}{6},
\]

and the theorem has been established. \(\Box\)

**Example 3.** We consider the IV-Fs \(Y, \mathcal{D} : [v, v + \zeta(\mu, v)] = [0, \zeta(1, 0)] \rightarrow \mathbb{K}^+_C\) defined by

\[
Y(\omega) = [2\omega^2, 4\omega^2]\quad\text{and}\quad\mathcal{D}(\omega) = [\omega, 2\omega].
\]

Since end point functions \(Y_s(\omega) = 2\omega^2\), \(Y^*(\omega) = 4\omega^2\) and \(\mathcal{D}_s(\omega) = \omega, \mathcal{D}^*(\omega) = 2\omega\) are preinvex functions with respect to \(\zeta(\mu, v) = \mu - v\). Hence \(Y, \mathcal{D}\) both are left and right preinvex IV-Fs. We now compute the following

\[
\frac{1}{\zeta(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y_s(\omega) \times \mathcal{D}_s(\omega) d\omega = \frac{1}{7},
\]

\[
\frac{1}{\zeta(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y^*(\omega) \times \mathcal{D}^*(\omega) d\omega = 2,
\]

\[
A_s((v, \mu)) = \frac{1}{7},
\]

\[
A^*((v, \mu)) = \frac{2}{3},
\]

\[
C_s((v, \mu)) = 0,
\]

\[
C^*((v, \mu)) = \frac{1}{6},
\]

that means

\[
\frac{1}{7} \leq \frac{2}{3}, \quad 2 \leq \frac{8}{3}.
\]

Hence, Theorem 4 is verified.

**Theorem 5.** Let \(Y, \mathcal{D} : [v, v + \zeta(\mu, v)] \rightarrow \mathbb{K}^+_C\) be two left and right preinvex IV-Fs, such that \(Y(\omega) = [Y_s(\omega), Y^*(\omega)]\) and \(\mathcal{D}(\omega) = [\mathcal{D}_s(\omega), \mathcal{D}^*(\omega)]\) for all \(\omega \in [v, v + \zeta(\mu, v)]\). If \(Y, \mathcal{D}\) and \(Y \times \mathcal{D} \in \mathcal{E}R([v, v + \zeta(\mu, v)])\) and condition \(C\) hold for \(\zeta\), then

\[
2Y \left( \frac{2v + \zeta(\mu, v)}{2} \right) \times \mathcal{D} \left( \frac{2v + \zeta(\mu, v)}{2} \right) \leq_p \frac{1}{\zeta(\mu, v)} (IR) \int_v^{v+\zeta(\mu, v)} Y(\omega) \times \mathcal{D}(\omega) d\omega + \frac{A(v, \mu)}{6} + \frac{C(v, \mu)}{3},
\]

where \(A(v, \mu) = Y(v) \times \mathcal{D}(v) + Y(\mu) \times \mathcal{D}(\mu), C(v, \mu) = Y(v) \times \mathcal{D}(\mu) + Y(\mu) \times \mathcal{D}(v),\) and \(A(v, \mu) = [A_s((v, \mu)), A^*((v, \mu))]\) and \(C(v, \mu) = [C_s((v, \mu)), C^*((v, \mu))].\)
Proof. Using condition C, we can write
\[ v + \frac{1}{2} \zeta(\mu, v) = v + \zeta(\mu, v) + \frac{1}{2} (v + (1 - t) \zeta(\mu, v), v + \zeta(\mu, v)). \]

By hypothesis, we have
\[
\begin{align*}
Y_s \left( \frac{2v + \zeta(\mu, v)}{2} \right) \times D_s \left( \frac{2v + \zeta(\mu, v)}{2} \right) \\
Y^* \left( \frac{2v + \zeta(\mu, v)}{2} \right) \times D^* \left( \frac{2v + \zeta(\mu, v)}{2} \right)
\end{align*}
\]
\[
= Y_s \left( v + \zeta(\mu, v) + \frac{1}{2} (v + (1 - t) \zeta(\mu, v), v + \zeta(\mu, v)) \right) \\
\times D_s \left( v + \zeta(\mu, v) + \frac{1}{2} (v + (1 - t) \zeta(\mu, v), v + \zeta(\mu, v)) \right) \\
= Y^* \left( v + \zeta(\mu, v) + \frac{1}{2} (v + (1 - t) \zeta(\mu, v), v + \zeta(\mu, v)) \right) \\
\times D^* \left( v + \zeta(\mu, v) + \frac{1}{2} (v + (1 - t) \zeta(\mu, v), v + \zeta(\mu, v)) \right)
\]

Integrating over \([0, 1]\), we have
\[
2 \left( \frac{2v + \zeta(\mu, v)}{2} \right) \times D \left( \frac{2v + \zeta(\mu, v)}{2} \right) \leq \frac{1}{\zeta(\mu, v)} \int_{0}^{v + \zeta(\mu, v)} Y_s(\omega) \times D_s(\omega) d\omega + \frac{A^*(v, \mu)}{6} + \frac{C_s(v, \mu)}{3},
\]
\[
2 \left( \frac{2v + \zeta(\mu, v)}{2} \right) \times D^* \left( \frac{2v + \zeta(\mu, v)}{2} \right) \leq \frac{1}{\zeta(\mu, v)} \int_{0}^{v + \zeta(\mu, v)} Y^*(\omega) \times D^*(\omega) d\omega + \frac{A^*(v, \mu)}{6} + \frac{C_s(v, \mu)}{3},
\]
from which, we have
\[
2 \left( \frac{2v + \zeta(\mu, v)}{2} \right) \times D \left( \frac{2v + \zeta(\mu, v)}{2} \right) \leq \frac{1}{r \zeta(\mu, v)} \int_{0}^{v + \zeta(\mu, v)} Y_s(\omega) \times D_s(\omega) d\omega + \frac{A^*(v, \mu)}{6} + \frac{C_s(v, \mu)}{3},
\]
that is
2Y\left(\frac{2v + \zeta(\mu, v)}{2}\right) \times D\left(\frac{2v + \zeta(\mu, v)}{2}\right) \leq p \frac{1}{\zeta(\mu, v)} (IR) \int_v^{v + \zeta(\mu, v)} Y(\omega) \times D(\omega)d\omega + \frac{A(v, \mu)}{6} + \frac{C(v, \mu)}{3}.

This completes the proof. □

**Example 4.** We consider the IV-Fs $Y, D : [v, v + \zeta(\mu, v)] \rightarrow \mathcal{K}^+_\mathcal{C}$ defined by, $Y(\omega) = [2\omega^2, 4\omega^2]$ and $D(\omega) = [1, 2\omega]$, and these functions fulfill all the assumptions of Theorem 5. Since $Y(\omega), D(\omega)$ both are left and right preinvex IV-Fs with respect to $\zeta(\mu, v) = \mu - v$, we have $Y_*(\omega) = 2\omega^2, Y^*(\omega) = 4\omega^2$ and $D_*(\omega) = \omega, D^*(\omega) = 2\omega$. We now compute the following

\[
\begin{align*}
2Y_*\left(\frac{2v + \zeta(\mu, v)}{2}\right) \times D_*\left(\frac{2v + \zeta(\mu, v)}{2}\right) &= \frac{1}{2}, \\
2Y^*\left(\frac{2v + \zeta(\mu, v)}{2}\right) \times D^*\left(\frac{2v + \zeta(\mu, v)}{2}\right) &= 2, \\
\frac{1}{\zeta(\mu, v)} \int_v^{v + \zeta(\mu, v)} Y_*(\omega) \times D_*(\omega)d\omega &= \frac{1}{2}, \\
\frac{1}{\zeta(\mu, v)} \int_v^{v + \zeta(\mu, v)} Y^*(\omega) \times D^*(\omega)d\omega &= 2,
\end{align*}
\]

that means

\[
\begin{align*}
\frac{1}{2} &\leq \frac{1}{2} + 0 + \frac{1}{2} = \frac{5}{6}, \\
\frac{1}{2} &\leq 2 + 0 + \frac{4}{3} = \frac{10}{3}.
\end{align*}
\]

Hence, Theorem 5 is verified.

It is well known that classical Hermite–Hadamard inequality is a generalization of classical Hermite–Hadamard inequality. Now we derive Hermite–Hadamard–Fejér inequality for left and right preinvex IV-Fs and then we will obtain the validity of this inequality with the help of a non-trivial example. Firstly, we obtain the second Hermite–Hadamard–Fejér inequality for left and right preinvex IV-F.

**Theorem 6.** Let $Y : [v, v + \zeta(\mu, v)] \rightarrow \mathcal{K}^+_\mathcal{H}$ be a left and right preinvex IV-F with $v < v + \zeta(\mu, v)$ such that $Y(\omega) = [Y_*(\omega), Y^*(\omega)]$ for all $\omega \in [v, v + \zeta(\mu, v)]$. If $Y \in \mathcal{T}R_{\mathcal{C}}[v, v + \zeta(\mu, v)]$ and $S : [v, v + \zeta(\mu, v)] \rightarrow \mathbb{R}, S(\omega) \geq 0$, symmetric with respect to $v + \frac{1}{2}\zeta(\mu, v)$, then

\[
\frac{1}{\zeta(\mu, v)} (IR) \int_v^{v + \zeta(\mu, v)} Y(\omega) S(\omega)d\omega \leq p [Y(v) + Y(\mu)] \int_0^1 tS(v + t\zeta(\mu, v))dt. \tag{17}
\]

**Proof.** Let $Y$ be a left and right preinvex IV-F. Then, we have

\[
\begin{align*}
Y_*(v + (1 - t)\zeta(\mu, v))S(v + (1 - t)\zeta(\mu, v)) &\leq ((1 - t)Y_*(v) + tY_*(\mu))S(v + (1 - t)\zeta(\mu, v)), \\
Y^*(v + (1 - t)\zeta(\mu, v))S(v + (1 - t)\zeta(\mu, v)) &\leq ((1 - t)Y^*(v) + tY^*(\mu))S(v + (1 - t)\zeta(\mu, v)).
\end{align*}
\]

And

\[
\begin{align*}
Y_*(v + t\zeta(\mu, v))S(v + t\zeta(\mu, v)) &\leq ((1 - t)Y_*(v) + tY_*(\mu))S(v + t\zeta(\mu, v)), \\
Y^*(v + t\zeta(\mu, v))S(v + t\zeta(\mu, v)) &\leq ((1 - t)Y^*(v) + tY^*(\mu))S(v + t\zeta(\mu, v)).
\end{align*}
\]
After adding (18) and (19), and integrating over [0, 1], we get

\[
\int_0^1 Y_s(v + (1 - t)\zeta(\mu, v))S(v + (1 - t)\zeta(\mu, v))dt \\
+ \int_0^1 Y_s(v + t\zeta(\mu, v))S(v + t\zeta(\mu, v))dt \\
\leq \int_0^1 \left[ Y_s(v)\{tS(v + (1 - t)\zeta(\mu, v)) + (1 - t)S(v + t\zeta(\mu, v))\} \\
+ Y_s(\mu)\{(1 - t)S(v + (1 - t)\zeta(\mu, v)) + tS(v + t\zeta(\mu, v))\} \right]dt,
\]

\[
\int_0^1 Y^*(v + (1 - t)\zeta(\mu, v))S(v + (1 - t)\zeta(\mu, v))dt \\
+ \int_0^1 Y^*(v + t\zeta(\mu, v))S(v + t\zeta(\mu, v))dt \\
\leq \int_0^1 \left[ Y^*(v)\{tS(v + (1 - t)\zeta(\mu, v)) + (1 - t)S(v + t\zeta(\mu, v))\} \\
+ Y^*(\mu)\{(1 - t)S(v + (1 - t)\zeta(\mu, v)) + tS(v + t\zeta(\mu, v))\} \right]dt.
\]

Since \( S \) is symmetric, then

\[
= 2[Y_s(v) + Y_s(\mu)] \int_0^1 tS(v + t\zeta(\mu, v)) dt, \quad (20)
\]

\[
= 2[Y^*(v) + Y^*(\mu)] \int_0^1 tS(v + t\zeta(\mu, v)) dt.
\]

Since

\[
\int_0^1 Y_s(v + (1 - t)\zeta(\mu, v))S(v + (1 - t)\zeta(\mu, v))dt \\
= \int_0^1 Y_s(v + t\zeta(\mu, v))S(v + t\zeta(\mu, v))dt \\
= \frac{1}{\xi(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y_s(\omega)S(\omega)d\omega, \\
\int_0^1 Y^*(v + (1 - t)\zeta(\mu, v))S(v + (1 - t)\zeta(\mu, v))dt \\
= \int_0^1 Y^*(v + t\zeta(\mu, v))S(v + t\zeta(\mu, v))dt \\
= \frac{1}{\xi(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y^*(\omega)S(\omega)d\omega.
\]

From (21), we have

\[
\frac{1}{\xi(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y_s(\omega)S(\omega)d\omega \leq [Y_s(v) + Y_s(\mu)] \int_0^1 tS(v + t\zeta(\mu, v)) dt, \\
\frac{1}{\xi(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y^*(\omega)S(\omega)d\omega \leq [Y^*(v) + Y^*(\mu)] \int_0^1 tS(v + t\zeta(\mu, v)) dt,
\]

that is

\[
\left[ \frac{1}{\xi(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y_s(\omega)S(\omega)d\omega, \frac{1}{\xi(\mu, v)} \int_v^{v+\zeta(\mu, v)} Y^*(\omega)S(\omega)d\omega \right] \\
\leq_p [Y_s(v) + Y_s(\mu), Y^*(v) + Y^*(\mu)] \int_0^1 tS(v + t\zeta(\mu, v)) dt
\]

hence

\[
\frac{1}{\xi(\mu, v)} (IR) \int_v^{v+\zeta(\mu, v)} Y(\omega)S(\omega)d\omega \leq_p [Y(v) + Y(\mu)] \int_0^1 tS(v + t\zeta(\mu, v)) dt.
\]

\[\square\]

Now, we present the succeeding reformatory version of the generalized version of first \(\mathcal{H}\)-\(\mathcal{H}\)-Fejér inequalities for left and right preinvex IV-Fs.

**Theorem 7.** Let \( Y : [v, v + \zeta(\mu, v)] \rightarrow \mathcal{K}_+ \) be a left and right preinvex IV-F with \( v < v + \zeta(\mu, v) \) such that \( Y(\omega) = [Y_s(\omega), Y^*(\omega)] \) for all \( \omega \in [v, v + \zeta(\mu, v)] \). If \( Y \in \mathcal{F}(v, v + \zeta(\mu, v)) \) and \( S : [v, v + \zeta(\mu, v)] \rightarrow \mathbb{R}, S(\omega) \geq 0, \) symmetric with respect to \( v + \frac{1}{2}\zeta(\mu, v) \), and \( \int_v^{v+\zeta(\mu, v)} S(\omega)d\omega > 0, \) and Condition C for \( \zeta \), then

\[
Y\left(v + \frac{1}{2}\zeta(\mu, v)\right) \leq_p \frac{1}{\int_v^{v+\zeta(\mu, v)} S(\omega)d\omega} (IR) \int_v^{v+\zeta(\mu, v)} Y(\omega)S(\omega)d\omega.
\] (22)
**Proof.** Using condition C, we can write
\[ v + \frac{1}{2} \zeta(\mu, v) = v + t \zeta(\mu, v) + \frac{1}{2} \zeta(v + (1-t) \zeta(\mu, v)), \]

Since \( Y \) is a left and right preinvex, we have
\[
\begin{align*}
Y_s \left( v + \frac{1}{2} \zeta(\mu, v) \right) &= Y_s \left( v + t \zeta(\mu, v) + \frac{1}{2} \zeta(v + (1-t) \zeta(\mu, v)), v + t \zeta(\mu, v) \right) \\
&\leq \frac{1}{2} \left( Y_s(v + (1-t) \zeta(\mu, v)) + Y_s(v + t \zeta(\mu, v)) \right), \\
Y^s \left( v + \frac{1}{2} \zeta(\mu, v) \right) &= Y^s \left( v + t \zeta(\mu, v) + \frac{1}{2} \zeta(v + (1-t) \zeta(\mu, v)), v + t \zeta(\mu, v) \right) \\
&\leq (Y^s(v + (1-t) \zeta(\mu, v)) + Y^s(v + t \zeta(\mu, v))).
\end{align*}
\]

By multiplying (23) by \( S(v + (1-t) \zeta(\mu, v)) = S(v + t \zeta(\mu, v)) \) and integrating it by \( t \) over \([0, 1]\), we obtain
\[
\begin{align*}
\frac{1}{2} \left( \int_0^1 Y_s(v + (1-t) \zeta(\mu, v))S(v + (1-t) \zeta(\mu, v))dt \\
+ \int_0^1 Y_s(v + t \zeta(\mu, v))dtS(v + t \zeta(\mu, v)) \\
Y^s(v + \frac{1}{2} \zeta(\mu, v)) \int_0^1 S(v + t \zeta(\mu, v))dt \\
+ \int_0^1 Y^s(v + t \zeta(\mu, v))S(v + t \zeta(\mu, v))dt \right) \\
&\leq \frac{1}{2} \left( \int_0^1 Y^s(v + (1-t) \zeta(\mu, v))S(v + (1-t) \zeta(\mu, v))dt \\
+ \int_0^1 Y^s(v + t \zeta(\mu, v))S(v + t \zeta(\mu, v))dt \right) \int_0^1 S(v + t \zeta(\mu, v))dt.
\end{align*}
\]

Since
\[
\begin{align*}
\int_0^1 Y_s(v + (1-t) \zeta(\mu, v))S(v + (1-t) \zeta(\mu, v))dt \\
= \int_0^1 Y_s(v + t \zeta(\mu, v))S(v + t \zeta(\mu, v))dt \\
= \frac{1}{\zeta(\mu, v)} \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y_s(\omega)S(\omega)d\omega \\
= \int_0^1 Y^s(v + t \zeta(\mu, v))S(v + t \zeta(\mu, v))dt \\
= \frac{1}{\zeta(\mu, v)} \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y^s(\omega)S(\omega)d\omega.
\end{align*}
\]

From (25), we have
\[
\begin{align*}
Y_s \left( v + \frac{1}{2} \zeta(\mu, v) \right) &\leq \frac{1}{\int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} S(\omega)d\omega} \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y_s(\omega)S(\omega)d\omega, \\
Y^s \left( v + \frac{1}{2} \zeta(\mu, v) \right) &\leq \frac{1}{\int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} S(\omega)d\omega} \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y^s(\omega)S(\omega)d\omega.
\end{align*}
\]

From which, we have
\[
\begin{align*}
\leq \frac{1}{\int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} S(\omega)d\omega} \left[ \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y_s(\omega)S(\omega)d\omega, \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y^s(\omega)S(\omega)d\omega \right],
\end{align*}
\]

that is
\[
\begin{align*}
Y \left( v + \frac{1}{2} \zeta(\mu, v) \right) &\leq \frac{1}{\int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} S(\omega)d\omega} \left( IR \int_{\zeta(\mu, v)}^{v+\zeta(\mu, v)} Y(\omega)S(\omega)d\omega. \right)
\end{align*}
\]

This completes the proof. \( \square \)

**Remark 5.** If one considers taking \( \zeta(\mu, v) = \mu - v \), then, by combining inequalities (17) and (22), we achieve the expected inequality.

If one considers taking \( Y_s(\omega) = Y^s(\omega) \), then, by combining inequalities (17) and (22), we achieve the classical \( \mathcal{I}-\mathcal{I}-\text{Fejér} \) inequality, see [30].
If one considers taking \( Y_\sigma(\omega) = Y^\sigma(\omega) \) and \( \zeta(\mu, \nu) = \nu - \mu \), then, by combining inequalities (17) and (22), we acquire the classical \( \mathcal{M}\mathcal{M}\)-Fejér inequality, see [33].

**Example 5.** We consider the IV-F \( Y : [1, 1 + \zeta(4, 1)] \to K_+^\omega \) defined by \( Y(\omega) = [2, 4]e^{\omega} \). Since end point functions \( Y_\sigma(\omega), Y^\sigma(\omega) \) are preinvex functions \( \zeta(\sigma, \omega) = \sigma - \omega \), then, \( Y(\omega) \) is left and right preinvex IV-F. If

\[
\mathcal{S}(\omega) = \begin{cases} 
\omega - 1, & \sigma \in [1, \frac{3}{2}], \\
4 - \omega, & \sigma \in \left(\frac{5}{2}, 4\right].
\end{cases}
\]

Then, we have

\[
\begin{align*}
\frac{1}{\zeta(4, 1)} \int_1^{1+\zeta(4, 1)} Y_\sigma(\omega) \mathcal{S}(\omega) d\omega &= \frac{1}{3} \int_1^{3} Y_\sigma(\omega) \mathcal{S}(\omega) d\omega + \frac{2}{3} \int_1^{3} Y^\sigma(\omega) \mathcal{S}(\omega) d\omega \\
\frac{1}{\zeta(4, 1)} \int_1^{1+\zeta(4, 1)} Y^\sigma(\omega) \mathcal{S}(\omega) d\omega &= \frac{1}{3} \int_1^{3} Y_\sigma(\omega) \mathcal{S}(\omega) d\omega + \frac{2}{3} \int_1^{3} Y^\sigma(\omega) \mathcal{S}(\omega) d\omega,
\end{align*}
\]

(26)

and

\[
\begin{align*}
[Y_\sigma(\nu) + Y_\sigma(\mu)] \int_0^1 t \mathcal{S}(v + t\zeta(\mu, \nu)) dt & \quad [Y^\sigma(\nu) + Y^\sigma(\mu)] \int_0^1 t \mathcal{S}(v + t\zeta(\mu, \nu)) dt \\
= 2[3e + e^4] & \quad \left[ \int_0^1 3\nu^2 d\omega + \int_0^1 \nu^2(3 - 3t) dt \right] \approx 43.
\end{align*}
\]

(27)

From (26) and (27), we have

\[
[22, 44] \leq [43, 86].
\]

Hence, Theorem 6 is verified. For Theorem 7, we have

\[
\begin{align*}
Y_\sigma\left(\nu + \frac{1}{2}\zeta(\mu, \nu)\right) & \approx \frac{122}{5}, \\
Y^\sigma\left(\nu + \frac{1}{2}\zeta(\mu, \nu)\right) & \approx \frac{244}{5},
\end{align*}
\]

(28)

\[
\int_{\nu}^{\nu+\zeta(\mu, \nu)} \mathcal{S}(\omega) d\omega = \int_1^{3} (\omega - 1) d\omega + \int_1^{3} (4 - \omega) d\omega = \frac{9}{4},
\]

\[
\frac{1}{\int_{\nu}^{\nu+\zeta(\mu, \nu)} \mathcal{S}(\omega) d\omega} \int_1^{3} Y_\sigma(\omega) \mathcal{S}(\omega) d\omega \approx \frac{146}{5},
\]

\[
\frac{1}{\int_{\nu}^{\nu+\zeta(\mu, \nu)} \mathcal{S}(\omega) d\omega} \int_1^{3} Y^\sigma(\omega) \mathcal{S}(\omega) d\omega \approx \frac{293}{5}
\]

(29)

From (28) and (29), we have

\[
\left[ \frac{122}{5}, 49 \right] \leq p \left[ \frac{146}{5}, \frac{293}{5} \right].
\]

Hence, Theorem 7 is verified.

### 4. Conclusions and Prospective Results

In this study, the notion of left and right preinvex functions in interval-valued settings was presented. For left and right preinvex interval-valued functions, we constructed Hermite–Hadamard type inequalities, as well as for the product of two left and right preinvex interval-valued functions. We also established Hermite–Hadamard–Fejér type...
inequality. We also discussed some special cases and provided some examples to prove the validity of our main results. In future, we will seek to explore this concept by using different fractional integral operators, such as Riemann–Liouville fractional operators, Katugampola fractional operators and generalized K-fractional operators.

Finally, we think that our results may be relevant to other fractional calculus models having Mittag–Leffler functions in their kernels, such as Atangana–Baleanu and Prabhakar fractional operators. This consideration has been presented as an open problem for academics interested in this topic. Researchers who are interested might follow the steps outlined in the references [54,55].

**Author Contributions:** Conceptualization, M.B.K.; methodology, M.B.K.; validation, S.T., M.S.S. and H.G.Z.; formal analysis, K.N.; investigation, M.S.S.; resources, S.T.; data curation, H.G.Z.; writing—original draft preparation, M.B.K., K.N. and H.G.Z.; writing—review and editing, M.B.K. and S.T.; visualization, H.G.Z.; supervision, M.B.K. and M.S.S.; project administration, M.B.K.; funding acquisition, K.N., M.S.S. and H.G.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors would like to thank the Rector, COMSATS University Islamabad, Islamabad, Pakistan, for providing excellent research support. This work was funded by Taif University Researchers Supporting Project number (TURSP-2020/345), Taif University, Taif, Saudi Arabia. In addition, this research has received funding support from the National Science, Research and Innovation Fund (NSRF), Thailand.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


25. Lupulescu, V. Fractional calculus for interval-valued functions. Fuzzy Syst. Sets. 2015, 265, 63–85. [CrossRef]


32. Khan, M.B.; Noor, M.A.; Noor, K.I.; Chu, Y.M. New Hermite-Hadamard type inequalities for -convex fuzzy-interval-valued functions. Axioms 2021, 10, 175. [CrossRef]


37. Khan, M.B.; Noor, M.A.; Noor, K.I.; Chu, Y.M. New Hermite-Hadamard type inequalities for -convex fuzzy-interval-valued functions. Axioms 2021, 10, 175. [CrossRef]

52. Khan, M.B.; Mohammed, P.O.; Machado, J.A.T.; Guirao, J.L. Integral Inequalities for Generalized Harmonically Convex Functions in Fuzzy-Interval-Valued Settings. Symmetry 2021, 13, 2352. [CrossRef]