**Field Pea Performance in Relation to Agrometeorological Indices Across Different Environments**

**ABSTRACT**

An agro-meteorological investigation was undertaken during *Rabi* Season *(*2019-20) at Farm, Department of NRM, College of Forestry, SHUATS, Prayagraj State (India). The experiment followed split plot design (SPD) with three replications, included 27 treatment combinations based on three sowing windows—46th meteorological week (MW) (November 12–18, D1), 48th MW (November 26–December 2, D2), and 50th MW (December 10–16, D3)—as the main plot factor and three field pea varieties viz. Rachana (V1), Malviya-15 (HUDP-15) (V2), and Aparna (V3)—as the sub-plot factor, and among the sowing dates, the early sown crop (D1) accumulated the highest growing degree days (GDD), heliothermal units (HTU), and photothermal units (PTU), resulting in the longest seed development duration (SDD). Among the cultivars highest SDD was found in Rachana while the GDD, PTU was found highest in Malviya-matar and HTU was observed in Aparna Variety.

**Key Word*:*** Field Pea, GDD, HTU, PTU and SDD

**INTRODUCTION**

Pea (*Pisum sativum* L.), a member of the Fabaceae (Leguminosae) family, is an agriculturally and nutritionally significant cool-season legume cultivated worldwide. Field pea is an important crop both economically and nutritionally, often referred to as the “poor man’s meat” because it offers an affordable source of protein, essential vitamins, minerals, and prebiotic carbohydrates for low-income populations (**Amarakoon et al., 2012**). Notably, it is naturally high in iron and zinc, making it a valuable food source for combating two of the most widespread micronutrient deficiencies globally (**Amarakoon et al., 2012**).

Field pea thrives in cool growing conditions, with an optimal temperature range of 10°C to 25°C for proper growth and development. Temperatures exceeding this range, particularly during flowering and pod formation, can adversely affect seed set and yield. The base temperature for germination is approximately 4°C–5°C, while vegetative growth occurs efficiently between 5°C and 7°C. The crop performs best in well-drained loamy soils with a pH of 6.0–7.5 and is highly sensitive to waterlogging. Field pea is categorized as a long-day plant, with most genotypes exhibiting a quantitative response to photoperiod **(Foyer et al., 2016)**

India is the fourth-largest country in terms of area under pea cultivation, followed by Canada, China, and the former USSR. Among the Indian states, Uttar Pradesh, Madhya Pradesh, and Maharashtra are the primary producers of garden peas. Notably, Uttar Pradesh accounts for nearly 50% of the total area and production of vegetable peas in the country (**Pandey et al., 2017**). As per data from the National Horticulture Board **(2018–2019),** peas are cultivated over approximately 554 thousand hectares in India, yielding an annual production of around 5.52 million metric tonnes. Globally, dry and green pea production is reported across 85 countries, with annual production exceeding 40 million tonnes (**FAOSTAT, 2019**). Major dry pea-producing nations include the Canada (4.2 million ha), Russia (2.4 million ha), China (1.5 million ha), India (0.8 million ha), and France (0.79 million ha).

The growth and development of field pea are strongly influenced by temperature (**Hodges, 1991; Ritchie & Ne Smith, 1991**) and photoperiod (**Omanga et al., 1996**). Studies indicate that temperature can have an impact on the developmental rate of field pea comparable to that of photoperiod. The optimal temperature range for its growth is 18°C–24°C (**Van der Maesen, 1989**).

Several weather-based indices, including Growing Degree Days (GDD), Helio-Thermal Units (HTU), and Photo-Thermal Units (PTU), are used to evaluate crop growth and development. GDD quantifies heat accumulation necessary for different phenological stages, establishing a correlation between temperature and crop growth duration. HTU considers the effect of fluctuating temperatures on the time interval between phenological events, facilitating comparisons of crop responses across different thermal environments. These indices are essential for understanding crop adaptation to climatic variability and optimizing sowing strategies for improved yield.

**MATERIALS AND METHODS**

**Location of the Research Site**

The experiment was conducted during the Rabi season of 2019–20 at the Forest Nursery, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh. The experimental site is geographically located at 25.57°N latitude, 81.50°E longitude, with an altitude of 98 meters above mean sea level (MSL).

The field experiment followed a split plot design design (SPD) with three replications. The study comprised 27 treatment combinations, consisting of three sowing dates viz. November 15 (D1), November 30 (D2), and December 15(D3) as main plot treatments and three field pea varieties viz. Rachana (V1), Malviya Matar-15 (V2), and Aparna(V3) as sub-plot treatments. The gross and net plot sizes were 151.9 m² and 108 m², respectively. A plant spacing of 60 cm × 20 cm was maintained, with a seed rate of 100 kg ha⁻¹. A recommended fertilizer dose of 25:50:30 kg N, P, K ha⁻¹ was uniformly applied across all treatments to ensure optimal crop nutrition.

**Computation of Agro meteorological indices**

**Growing degree days (GDD)**

Growing Degree Days (GDD) were calculated using a base temperature of **5°C**, as per the method outlined by **Patel et al. (1999)**. The cumulative GDD for different phenological stages was determined using the following formula:

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Where:

Tmax​ = Daily maximum temperature (°C)

Tmin​ = Daily minimum temperature (°C)

Tbase​ = Base temperature (5°C)

**Helio-Thermal Units (HTU)**

Helio-Thermal Units (HTU) represent the product of Growing Degree Days (GDD) and the actual duration of bright sunshine hours (BSS) recorded using a sunshine recorder. Unlike the photo-thermal unit (PTU), which considers the maximum possible sunshine duration, HTU accounts for the actual sunlight received during a given period, making it a more precise indicator of the thermal and radiative energy available for crop growth. HTU is calculated using the following formula:

**HTU=∑(GDD×BSS)**

where:

* **GDD** = Growing Degree Days (°C day)
* **BSS** = Actual bright sunshine hours (hours)

**Photo-Thermal Units (PTU)**

Photo-Thermal Units (PTU) represent the combined influence of temperature and photoperiod on crop growth and development. PTU is defined as the product of Growing Degree Days (GDD) and day length (DL), expressed in °C day hours. It serves as a key agro-meteorological index for assessing the impact of thermal and photoperiodic variations on plant phenology. PTU was calculated using the following formula, as proposed by **Gudadhe et al. (2013):**

**PTU=∑(GDD×DL)**

where:

* **GDD** = Growing Degree Days (°C day)
* **DL** = Day length (hours)

**Stress Degree Days Index(SDDI)**

Canopy temperature was measured using an infrared thermometer, while air temperature was simultaneously recorded at approximately 1 meter above the crop canopy. Measurements were taken from four points within each plot, and the average value was used for analysis. These temperature readings were utilized to compute the Stress Degree Day (SDD), an indicator of crop heat stress.

The **basic formula for SDD** is:

**SDDI = (Tc-Ta)** (**Idso *et al* 1977**)

Whereas,

Tc= Midday canopy temperature

Ta= Midday air temperature

**RESULTS AND DISCUSSION**

**Phenological studies**

Phenology refers to the sequential study of developmental stages or crop growth phases. The duration (in days) for the commencement of different phenological stages—such as **Sowing to Emergence (P1)**, **Vegetative Growth (P2)**, **Branching to Flowering (P3)**, **Flowering to Pod Formation (P4)**, and **Dough Stage to Maturity (P5)**—was observed across varying sowing dates of the field pea crop. The total duration from sowing to maturity ranged from **105 to 115 days**. The duration of the crop varied with different sowing dates and varieties, primarily due to the influence of weather conditions, which played a dominant role during different phenophases of field pea. Notably, the crop sown in the **46th MW** took a longer time to reach maturity compared to those sown in the **48th MW** and **50th MW**. Among the varieties, **Aparna** required the most days to mature. The shorter growth period in later sowing dates appeared to adversely affect both yield and total biomass production.

**YIELD**

Results from Table 1 indicate that both seed and straw yields were significantly affected by different treatments, particularly sowing dates and varieties. The highest seed (1424 kg ha⁻¹) and straw (1823 kg ha⁻¹) yields were observed when field pea was sown during the 48th meteorological week (MW), followed by the 46th and 50th MW sowings, in decreasing order.

Varietal differences also had a significant impact on yield. Aparna (V3) outperformed other varieties, producing the highest seed (1474 kg ha⁻¹) and straw (1881 kg ha⁻¹) yields. In contrast, Rachana (V1) recorded the lowest seed yield (1225 kg ha⁻¹), while Malviya-Matar(V2) yielded the least straw (1658 kg ha⁻¹). The superior performance of Aparna can be attributed to reduced flower drop, increased branching, and a higher number of pods per plant, all of which contributed to enhanced seed production.

Additionally, the interaction between sowing dates and varieties had a significant effect on both seed and straw yields, highlighting the importance of optimizing planting time based on cultivar selection.

**Table 1: Seed yield, straw yield (kg/ha), of field pea as influenced by different dates of sowing and varieties**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Seed yield** | | | | **Straw yield** | | | |
| **Treatment** |  | | | | | | |  |
| **D/V** | **V1** | **V2** | **V3** | **Mean** | **V1** | **V2** | **V3** | **Mean** |
| **D1** | 1286 | 1207 | 1524 | 1339 | 1806 | 1648 | 1990 | 1815 |
| **D2** | 1288 | 1416 | 15.68 | 1424 | 1665 | 1808 | 1998 | 1823 |
| **D3** | 1101 | 1201 | 1331 | 1211 | 1518 | 1518 | 1657 | 1564 |
| **Mean** | 1225 | 1275 | 1474 |  | 1663 | 1658 | 1881 |  |
|  | CD at 5% | | S.E. m (±) |  | CD at 5% | | S.E. m (±) |  |
| **DATE** | 0.652 | | 0.215 |  | 0.583 | | 0.193 |  |
| **VARIETY** | 0.652 | | 0.215 |  | 0.583 | | 0.193 |  |
| **INTERACTION** | NS | | 0.373 |  | 1.009 | | 0.334 |  |

**Agro meteorological indices**

Field pea (*Pisum sativum* L.) is cultivated across tropical, subtropical, and temperate regions, where weather conditions significantly influence crop productivity. Among climatic factors, temperature, bright sunshine hours (BSS), and humidity are critical in determining optimal sowing time and the duration of various phenological stages, ultimately affecting yield. Therefore, precise knowledge of developmental phases and their relationship with yield determining traits is crucial for maximizing productivity. To quantify crop growth and development, thermal indices such as Growing Degree Days (GDD), Helio-Thermal Units (HTU), Photo-Thermal Units (PTU) and Stress Degree Days (SDD) serve as reliable estimators, helping predict field pea growth stages under varying environmental conditions.

**Growing Degree Days (GDD)**

Table 2 illustrates the growing degree days (GDD) required at different phenological stages for three field pea varieties (Rachana, Malviya-15, and Aparna) under varying sowing dates.

The highest GDD was recorded for 15th November sowing (8410.2), showing that early planting benefits from longer, warmer growing periods. GDD declined with later sowings (6214.0 in D2, 5293.1 in D3), indicating reduced growth duration due to cooler conditions. Among varieties, Malviya-15 (6688.75) had slightly higher GDD than Rachana, while Aparna recorded the lowest (6570.75), reflecting minor differences in thermal adaptability. Reproductive stages (P3–P5) consistently required the most GDD, highlighting their sensitivity to heat and the need for adequate thermal accumulation for optimal yield.Future studies could explore genotype-environment interactions to identify heat-resilient varieties for late-sown conditions. Consistent with findings from **Sunil et al. (2005)** and **Pashawar et al. (2024)**.

**Table 2: Growing degree days (GDD) at different phenological stages of different Field pea verities as affected by planting time V1 (Rachana).**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Growing degree days (GDD)** | | | | | | | | | | | | | | | | |  | |  | |
| **Treatment** | **Rachana (V1)** | | | | | **Malviya-15 (V2)** | | | | | | **Aparna (V3)** | | | | | | **Total** | | **Mean** | |
| **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | | **P2** | **P3** | **P4** | **P5** |  | |  | |
| **DATE OF SOWING** |  |  |  |  |  |  |  |  |  |  |  | |  |  |  |  |  | |  | |
| **15th November** | 108.5 | 409.25 | 440.65 | 751.65 | 1087.35 | 111.5 | 410.25 | 430.65 | 758.65 | 1097.35 | 111.5 | | 408.25 | 430.65 | 756.65 | 1097.35 | 8410.2 | | 560.68 | |
| **30th November** | 67.55 | 228.7 | 338.5 | 619.4 | 838.2 | 71.55 | 232.7 | 348.5 | 614.4 | 830.2 | 63.55 | | 222.7 | 318.5 | 604.4 | 815.2 | 6214.0 | | 414.27 | |
| **15th December** | 32.9 | 170.9 | 250.5 | 540 | 773.8 | 38.4 | 180.9 | 252.6 | 545.3 | 765.8 | 28.4 | | 181.9 | 250.6 | 535.3 | 745.8 | 5293.1 | | 352.87 | |
| **Total** | 208.95 | 808.85 | 1029.65 | 1911.05 | 2699.35 | 221.45 | 823.85 | 1031.75 | 1918.35 | 2693.35 | 203.45 | | 812.85 | 999.75 | 1896.35 | 2658.35 |  | |  | |
| **Grand Total** | 6657.85 | | | | | 6688.75 | | | | | | 6570.75 | | | | | |  | |  | |

|  |  |
| --- | --- |
| **P1- Sowing to Emergence** | **P2- Vegetative Growth (Branching)** |
| **P3- Branching to Flowering** | **P4- Flowering to Pod formation** |
| **P5- Dough stage to Maturity stage** |  |

**Helio Thermal unit**

Table 3 presents the Helio Thermal Unit (HTU) accumulation across different phenological stages of three field pea varieties (Rachana, Malviya-15, and Aparna) under varying sowing dates.

The 15th November sowing (D1) recorded the highest HTU (62,469.46), indicating optimal solar and thermal conditions, while HTU declined with delayed sowings (45,747.82 in D2, 39,794.16 in D3), suggesting reduced energy availability. Among varieties, Aparna (V3) had the highest HTU (50,103.36), followed by Malviya-15 (V2) with intermediate values (49,103.23), reflecting varietal differences in energy use efficiency. HTU demand peaked during later stages (P4–P5), with early sowing consistently offering the most favorable conditions for growth and yield. Future research could explore genotypic variations in HTU efficiency to identify climate-resilient varieties for late-sown conditions, a phenomenon previously documented by **Nagamani et al. (2015).**

**Table 3: HTU at different phenological stages of different Field Pea verities as affected by planting time**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Helio Thermal Unit (HTU)** | | | | | | | | | | | | | | | | | | |
| **Treatment** | **Rachana (V1)** | | | | | **Malviya-15 (V2)** | | | | | | **Aparna (V3)** | | | | |  |  |
| **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | | **P2** | **P3** | **P4** | **P5** | **Total** | **Mean** |
| **DATE OF SOWING** |  |  |  |  |  |  |  |  |  |  |  | |  |  |  |  |  |  |
| **15th November** | 908.14 | 3044.82 | 3110.98 | 5441.94 | 8230.48 | 966.73 | 3052.26 | 3040.38 | 5515.38 | 8306.93 | 965.89 | | 3037.38 | 3040.38 | 5500.84 | 8306.93 | 62469.46 | 4164.630667 |
| **30th November** | 514.75 | 1449.95 | 2274.72 | 4899.45 | 6244.59 | 586.3 | 1475.31 | 2341.92 | 4859.9 | 6184.99 | 509.67 | | 1411.91 | 2140.32 | 4780.8 | 6073.24 | 45747.82 | 3049.854667 |
| **15th December** | 181.27 | 1119.39 | 1625.74 | 3947.4 | 5811.23 | 211.58 | 1184.89 | 1639.37 | 3986.14 | 5751.15 | 156.48 | | 1191.44 | 3474.09 | 3913.04 | 5600.95 | 39794.16 | 2652.944 |
| **Total** | 1604.16 | 5614.16 | 7011.44 | 14288.8 | 20286.3 | 1764.61 | 5712.46 | 7021.67 | 14361.4 | 20243.1 | 1632.04 | | 5640.73 | 8654.79 | 14194.7 | 19981.1 |  |  |
| **Grand Total** | 48804.85 | | | | | 49103.23 | | | | | 50103.36 | | | | | |  |  |

|  |  |  |
| --- | --- | --- |
| **P1- Sowing to Emergence** | **P2- Vegetative Growth (Branching)** | **P3- Branching to Flowering** |
| **P4- Flowering to Pod formation** | **P5- Dough stage to Maturity stage** |  |

**Photo-Thermal Units (PTU)**

Analysis revealed significant variation in Photo-Thermal Unit (PTU) accumulation across all phenological stages among different sowing dates (Table 4). The total PTU requirement from emergence to physiological maturity showed considerable variation, ranging from 72,515 to 111,855 °C-day hours across the studied sowing treatments.

PTU accumulation decreased with delayed sowing—highest in D1 (111,855 °C-day hours), followed by D2 and D3—highlighting the impact of sowing time on thermal and photoperiodic needs. Among varieties, Malviya-15 (V2) recorded the highest PTU (89,668.23), while Aparna (V3) had the lowest (88,075.07) but performed well during pod-filling stages (P4–P5), making it suitable for short growing seasons. Rachana (V1) showed intermediate PTU but was highly sensitive to delayed sowing. Across all varieties, PTU increased from vegetative (P1–P2) to reproductive stages (P3–P5), with pod development (P4) most affected by planting date—early sowing had 25–30% higher PTU, crucial for seed quality and yield.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Photo thermal Unit (PTU)** | | | | | | | | | | | | | | | | | |
|  | **Rachana (V1)** | | | | | **Malviya-15 (V2)** | | | | | **Aparna (V3)** | | | | |  | |
| **Treatment** | **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | **P2** | **P3** | **P4** | **P5** | **Total** | **Mean** |
| **DATE OF SOWING** |  | | | | | | | | | | | | | | | | |
| **15th November** | 1443.05 | 5443.02 | 5860.64 | 9996.94 | 14461.75 | 1482.95 | 5456.32 | 5727.64 | 10090.04 | 14594.75 | 1482.95 | 5429.72 | 5727.64 | 10063.44 | 14594.75 | 111855.6 | 7457.04 |
| **30th November** | 898.41 | 3041.71 | 4502.05 | 8238.02 | 11148.06 | 951.61 | 3094.91 | 4635.05 | 8166.2 | 11041.66 | 845.21 | 2961.91 | 4236.05 | 8038.52 | 10829.5 | 82628.87 | 5508.591 |
| **15th December** | 450.73 | 2341.33 | 3431.85 | 7398 | 10601.06 | 526.08 | 2478.33 | 3460.62 | 7470.61 | 10491.46 | 389.08 | 2492.03 | 3433.22 | 7333.61 | 10217.46 | 72515.47 | 4834.365 |
| **Total** | 2792.2 | 10826.1 | 13794.5 | 25633 | 36210.9 | 2960.64 | 11029.6 | 13823.3 | 25726.9 | 36127.9 | 2717.24 | 10883.7 | 13396.9 | 25435.6 | 35641.7 |  |  |
| **Grand Total** | 89256.62 | | | | | 89668.23 | | | | | 88075.07 | | | | |  |  |

**Table 4: PTU at different phenological stages of different Field Pea verities as affected by planting**

|  |  |
| --- | --- |
| **P1- Sowing to Emergence** | **P2- Vegetative Growth (Branching)** |
| **P3- Branching to Flowering** | **P4- Flowering to Pod formation** |
| **P5- Dough stage to Maturity stage** |  |

**Stress Degree Days (SDD)**

The accumulated Stress Degree Days (SDD) determined various phenophases under different date of sowing are presented in Table 5. The result revealed that on an average field pea required SDD to attain its physiological maturity.

Field pea required varying Stress Degree Days (SDD) to reach maturity across different sowing dates, ranging from -4.79 to -6.49. Early sowing (15th Nov) had the lowest stress (-81.19 SDD), while late sowing (15th Dec) faced the highest stress (-97.28 SDD), with 20–30% more stress during reproductive stages (P3–P5). Among varieties, Rachana (V1) showed highest stress tolerance (-54.54 SDD), while Malviya-15 (V2) and Aparna (V3) recorded higher stress (-98.65 and -97.09 SDD). Stress peaked during flowering (P3), especially for late sowings, with Malviya-15 being the most stress-sensitive (-22.41 SDD). Early stages (P1–P2) experienced lower stress, but still higher in December sowings.

**Table 5: SDD at different phenological stages of different Field Pea verities as affected by planting time**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Stress Degree Days (SDD)** | | | | | | | | | | | | | | | | | |
| **Treatment** | **Rachana (V1)** | | | | | **Malviya-15 (V2)** | | | | | **Aparna (V3)** | | | | | **Total** |  |
| **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | **P2** | **P3** | **P4** | **P5** | **P1** | **P2** | **P3** | **P4** | **P5** | **Mean** |
| **DATE OF SOWING** |  | | | | | | | | | | | | | | | | |
| **15th November** | -1.63 | -2.38 | -2.3 | -1.8 | -2.1 | -7.38 | -7.23 | -6.95 | -7.93 | -8.1 | -7.78 | -4.53 | -6.8 | -7.15 | -7.13 | -81.19 | -5.41 |
| **30th November** | -2.1 | -2.73 | -3.1 | -3 | -3.43 | -3.7 | -5.1 | -7.43 | -6.66 | -4.05 | -3.5 | -4.88 | -7.28 | -6.1 | -8.75 | -71.81 | -4.79 |
| **15th December** | -6.08 | -5.93 | -4.78 | -5.3 | -7.88 | -5.3 | -7.88 | -8.03 | -6.33 | -6.58 | -6.05 | -8.05 | -7.28 | -6.13 | -5.68 | -97.28 | -6.49 |
| **Total** | -9.81 | -11.04 | -10.18 | -10.1 | -13.41 | -16.38 | -20.21 | -22.41 | -20.92 | -18.73 | -17.33 | -17.46 | -21.36 | -19.38 | -21.56 |  |  |
| **Grand Total** | -54.54 | | | | | -98.65 | | | | | -97.09 | | | | |  |  |

|  |  |  |
| --- | --- | --- |
| **P1- Sowing to Emergence** | **P2- Vegetative Growth (Branching)** | **P3- Branching to Flowering** |
| **P4- Flowering to Pod formation** | **P5- Dough stage to Maturity stage** |  |

**CONCLUSION**

The study revealed that field pea sown on the D2 sowing date (48th MW) and the Aparna cultivar exhibited superior grain yield, recording 1424 kg ha⁻¹ and 1474 kg ha⁻¹, respectively. Furthermore, key agro-meteorological indices, including growing degree days (GDD), helio-thermal units (HTU), and photo-thermal units (PTU), demonstrated a declining trend with delayed sowing. The findings also suggest that microclimatic variations induced by different sowing dates significantly influence the phenological progression of the crop. The observed variations in agro-meteorological parameters across different phenological stages indicate that cumulative thermal time can serve as a predictive tool for estimating biomass accumulation and crop yield.

**Data availability:** Data will be made available on request from corresponding author

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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