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Research Article

Impact of Selected Insect Pollinators on Yield and Physicochemical Quality of Apricot (*Prunus armeniaca* L.) and Apple (*Malus domestica* Borkh) in Doda District, Jammu and Kashmir (UT), India

Rohit Rohit, Anjali Dhar*

Department of Zoology, Central University of Jammu, Jammu and Kashmir, INDIA.

ABSTRACT

Background: Insect-mediated pollination is an indispensable ecosystem service for temperate fruit crop production. **Objectives:** This study tested the hypothesis that insect pollinators make a quantifiable, irreplaceable contribution to the fruit set and physicochemical quality of apricot (*Prunus armeniaca* L., cv. Halman and cv. Chuli) and apple (*Malus domestica* Borkh., cv. Red Delicious and cv. Ambri) in Doda district, Jammu and Kashmir (UT), India. **Materials and Methods:** Three pollination treatments were implemented across replicated orchard sites during the 2023 and 2024 spring flowering seasons: open pollination (natural insect visitation), self-pollination under mechanical exclusion (nylon netting), and hand cross-pollination (positive control). Pollinator visitation was recorded using standardized timed focal sampling from anthesis until flowering cessation, and a Pollinator Importance Value (PIV) was calculated for each taxon. Fruit set percentage was determined at 30 days post-anthesis, and physicochemical parameters including fruit weight, volume, Total Soluble Solids (TSS), Titratable Acidity (TA), ascorbic acid content, and colorimetric indices (L*, a*, b*) were measured at commercial maturity. **Results:** Open-pollinated flowers achieved significantly higher fruit set than mechanically excluded self-pollinated flowers in both apple (72.4±4.2% vs. 18.3±2.7%; $p<0.001$; Cohen's d=2.84) and apricot (64.7± 5.1% vs. 21.6±3.3%; $p<0.001$; d=1.97). Open-pollinated fruits were significantly heavier, had greater volume, and higher TSS and ascorbic acid content. *Apis mellifera* and *Apis cerana* dominated the pollinator community (PIV=0.338 and 0.243, respectively), with peak visitation between 10:00 and 14:00 hr. Pollinator visitation frequency was positively correlated with fruit set (r=0.82), fruit weight (r=0.74), and seed number per fruit (r=0.77). **Conclusion:** These findings establish insect pollinators as critical determinants of horticultural productivity in Doda district and provide an evidence base for pollinator conservation policy in J&K (UT).

Keywords: Doda, Fruit set, Indian Himalaya, Insect pollination, *Malus domestica*, *Prunus armeniaca*.

Correspondence:
Dr. Anjali Dhar
Assistant Professor, Department of Zoology, Central University of Jammu, Jammu and Kashmir-181143, INDIA.
Email: anjali.zool@cujammu.ac.in
ORCID: 0000-0002-4664-2645

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INTRODUCTION

Pollination by insects, primarily bees and allied hymenopteran taxa, is a critical ecological process that underpins the reproductive success and economic productivity of a broad spectrum of angiosperm crops globally. Estimates indicate that approximately 75% of leading food crop species depend either wholly or partially on animal-mediated pollination, with the global economic value of this service calculated to exceed several hundred billion USD annually (Klein *et al*., 2007). For temperate deciduous fruit crops belonging to the family Rosaceae, particularly species of Prunus and Malus, entomophilous pollination is not merely advantageous but often obligatory for commercially viable fruit set, given that these taxa exhibit varying degrees of self-incompatibility mediated by the S-locus gametophytic incompatibility system (Hancock *et al*., 2015). In this context, insect pollinators serve as the principal vectors of conspecific pollen transfer between genetically compatible cultivars, and their abundance and activity patterns during anthesis exert deterministic influence on fruit set percentages, seed content, and the downstream physicochemical attributes of mature fruits.

The Doda district, situated in the Jammu division of Jammu and Kashmir (UT), India, occupies a complex topographic and climatic zone within the outer western Himalayan ranges, with elevations spanning approximately 700-4,600 m above mean sea level. The district's agro-climatic conditions, characterized

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by cool temperate winters, moderate growing seasons, and a diverse floral mosaic, support extensive cultivation of apricot (*Prunus armeniaca* L.) and apple (*Malus domestica* Borkh.) as the economically dominant horticultural crops. Despite the socioeconomic significance of these species to local communities, empirical data quantifying the contribution of insect pollinators to their yield and quality in this specific agro-ecological context are conspicuously lacking in the peer-reviewed literature. Investigations conducted in comparable Himalayan systems, including those in Himachal Pradesh and the Kashmir Valley, have consistently demonstrated the irreplaceable role of *Apis cerana* F., *Apis mellifera* L., and various solitary bee species in driving fruit set in apple and other rosaceous crops (Abrol *et al*., 2019). Yet localized, district-level studies remain essential for informing geographically targeted conservation and management interventions.

Pollinator community composition and visitation frequency are influenced by a matrix of factors including landscape heterogeneity, floral resource availability, cropping system management, and prevailing climatic conditions during anthesis (Barbosa and Letourneau, 1988). In montane horticultural landscapes, the temporal overlap between insect pollinator activity peaks and crop anthesis windows is particularly critical, as late frosts, microclimatic temperature fluctuations, and phenological asynchrony can substantially reduce effective pollinator service delivery. The systematic exclusion of insect pollinators through mechanical barriers such as fine-mesh nylon netting, used in conjunction with open-pollination controls, represents a methodologically robust approach to quantifying the net pollinator contribution to fruit set and quality, as it permits direct attribution of observed differences to pollinator activity rather than to extraneous agronomic variables (Adamidis *et al*., 2019).

The present investigation was conceived to address the identified knowledge gap by: (i) characterizing the diversity, abundance, and temporal visitation patterns of insect pollinators in apricot and apple orchards of Doda district; (ii) quantitatively measuring the impact of insect pollinator exclusion versus free pollination on fruit set percentage; and (iii) determining the effect of pollination treatment on key physicochemical quality parameters of harvested fruits, including weight, volume, colour, total soluble solids, titratable acidity, and ascorbic acid content.

MATERIALS AND METHODS

Study Area and Site Selection

The study was conducted during the spring flowering seasons of 2023 and 2024 across selected orchard sites in the Doda district of Jammu and Kashmir (UT), India (geographical coordinates: approximately 32°42'-33°26'N, 75°14'-76°20'E). Three orchard sites were selected for each crop species, ensuring a minimum inter-site distance of 2 km to reduce spatial pseudoreplication and to capture micro-habitat variation representative of the district's topographic heterogeneity. Selected orchards were managed under conventional cultivation practices, were free from systemic insecticide applications during the study period, and comprised mature trees of known cultivar identity. Apricot sites consisted of orchards containing cv. Halman and cv. Chuli, the two commercially dominant apricot cultivars in Doda district, selected on the basis of regional prevalence and their documented partial self-incompatibility. Apple sites included orchards of cv. Red Delicious and cv. Ambri, selected on the basis of regional commercial prevalence and documented cross-pollination requirements.

Experimental Pollination Treatments

A controlled field experiment was implemented using three pollination treatment regimes applied to replicated branches within each orchard: (i) Open Pollination (OP), in which branches bearing a standardized complement of floral buds were left fully exposed to ambient insect pollinator communities and prevailing wind; (ii) Self-Pollination under mechanical exclusion (SP), in which floral clusters were individually enclosed in fine-mesh synthetic nylon netting bags (mesh aperture ≤0.2 mm) prior to anthesis to prevent insect visitation while permitting air exchange, light transmission, and self-pollen deposition mediated by anther dehiscence and gravitational transfer; and (iii) Hand Cross-Pollination (CP), in which branches were subjected to hand-emasculation at the tight-pink bud stage (BBCH 57) followed by controlled deposition of freshly collected pollen from a compatible donor cultivar (apricot: cv. Sufaid Sufaida; apple: cv. Golden Delicious), applied using a camel-hair brush at anthesis. CP nylon bags were reinstated immediately following hand-pollination and removed at confirmed fruit set. Nylon bag enclosures for SP branches were installed a minimum of 48 hr prior to the onset of anthesis and maintained until petal fall was complete and fruit set was confirmed.

A total of 320-340 individual flowers per treatment per orchard site were tagged at the bud stage across three spatially distinct branches per tree, with three trees per site per treatment, yielding a combined total of 2,880-3,060 tagged flowers per crop across both study seasons, producing nine orchard-treatment combinations per crop and 27 treatment-site-season replication units in total. Ambient air temperature (°C), relative humidity (%), and wind speed (m s^{-1}) were recorded at 30-min intervals using a portable automatic weather station (Davis Instruments Vantage Pro 2) installed at each orchard site throughout each anthesis season.

Pollinator Observation and Diversity Assessment

Pollinator visitation was quantified using standardized timed focal sampling, following established protocols for insect-flower interaction studies (Barbosa and Letourneau, 1988). Observations were conducted daily from 08:00 to 18:00 hr at 1-hr intervals beginning at first anthesis and continuing until complete cessation of flowering, operationally defined as the stage at which >95% of flowers within the monitored population had either set fruit or abscised. Each observation bout consisted of a continuous 15-min timed census of all insect visitors contacting reproductive floral organs within a standardized observation frame (2 m × 2 m canopy section). All visiting insect taxa were identified to species or morpho-species level, with voucher specimens collected using entomological aspirators, preserved in 70% ethanol, and deposited in the Entomology Reference Collection, Department of Zoology, Central University of Jammu (accession nos. CUJ-ENT-2023-001 to CUJ-ENT-2023-018). Visitation frequency (visits per flower per hour), visitation duration (seconds per floral visit), and stigmatic contact efficiency were recorded for each taxon and used to calculate a Pollinator Importance Value (PIV) as the product of relative visit frequency and stigmatic contact efficiency (Dafni, 1992).

Fruit Set and Yield Assessment

Fruit set was determined at 30 days post-anthesis as the percentage of tagged flowers per treatment that developed into persistent fruitlets exceeding 1 cm in polar diameter. Final yield per tree was estimated as the product of mean fruit set percentage, branch-level flower density, and mean individual fruit weight at commercial maturity. All fruits from tagged positions were harvested at commercial maturity, determined using cultivar-specific firmness thresholds and starch-iodine index values, and transported to the laboratory in refrigerated conditions (4°C) within 6 hr of harvest.

Physicochemical Quality Parameters

Physicochemical characterization of harvested fruits was conducted in accordance with established protocols in postharvest science (Adamidis *et al*., 2019). The following parameters were determined for a minimum of 30 individual fruits per treatment per site per crop: fruit weight (g) by calibrated digital analytical balance (precision: 0.01 g); fruit volume (cm^3) by water displacement volumetry; polar and equatorial diameter (mm) by digital Vernier calipers; fruit color by Minolta CR-400 colorimeter (CIE L*, a*, b* color space, D65 illuminant); Total Soluble Solids (TSS, °Brix) by digital refractometer (Atago PAL-1) at 20°C; titratable acidity (TA, % malic acid equivalent) by potentiometric titration against 0.1 N NaOH to endpoint pH 8.1; ascorbic acid content (mg/100 g fresh weight) by 2,6-Dichlorophenolindophenol (DCPIP) titrimetric method; and seed number per fruit by longitudinal dissection.

Statistical Analysis

All data were subjected to statistical analysis using R version 4.3.1 (R Core Team, 2023). Treatment differences in fruit set percentage were assessed by one-way Analysis of Variance (ANOVA) followed by Tukey's Honestly Significant Difference (HSD) post-hoc test (α=0.05) on arcsine square-root transformed data; results were verified by a Generalized Linear Mixed Model (GLMM) with binomial error distribution (glmer(), lme4; Bates *et al*., 2015). Physicochemical quality parameters were analysed by linear mixed-effects models (lmer(), lme4) with pollination treatment as a fixed factor, orchard site and tree nested within site as random intercept effects [(1|Site/Tree)], and crop season as a blocking variable; fixed-effect significance was assessed by Type III likelihood ratio tests. Pearson correlation coefficients were computed between pollinator visitation frequency and fruit set percentage, fruit weight, TSS, and seed number per fruit.

RESULTS

Insect Pollinator Diversity and Visitation Patterns

Across both crop species and all orchard sites, a total of 18 insect morpho-taxa were identified as flower visitors during the anthesis monitoring period. Hymenoptera collectively accounted for 87.4% of all recorded floral visits. *Apis mellifera* L. was the most abundant visitor at 41.2% of total visits, followed by *Apis cerana* F. at 28.6%. Solitary bee species comprising *Andrena* spp. (6.4%), *Osmia* spp. (5.1%), *Halictus* spp. (2.4%), and *Lasioglossum* spp. (1.4%) constituted 15.3% of total visits. Dipteran visitors (Syrphidae: *Episyrphus balteatus* De Geer, 5.2%; *Eristalis tenax* L., 3.2%) accounted for 8.4% of recorded visits but exhibited substantially lower stigmatic contact efficiency relative to hymenopteran visitors. The remaining 6.5% comprised *Bombus* spp. (3.2%), *Xylocopa* spp. (1.8%), and unidentified Diptera and Lepidoptera (1.5%). Pollinator Importance Values and detailed visitation metrics for the ten dominant taxa are presented in Table 1. *Apis mellifera* and *Apis cerana* attained the highest PIV scores across both crops (0.338 and 0.243, respectively). Despite contributing only 5.1% of total visits, *Osmia* spp. achieved a disproportionately high PIV (0.048) attributable to its elevated stigmatic contact efficiency (0.94).

Peak pollinator visitation was recorded between 10:00 and 14:00 hr across both crops, coinciding with maximal anther dehiscence and stigmatic receptivity. Mean visitation frequency for *Apis mellifera* on apple flowers was 6.8±0.9 visits per flower per hour, compared to 5.3±0.7 for *Apis cerana*. During seven frost event days recorded across the two apricot anthesis seasons (mean minimum temperature: -2.4°C), *Apis mellifera* foraging was completely suppressed while *Apis cerana* maintained visits at approximately 38% of non-frost-day frequencies. Complete cessation of flowering was observed by day 22 post-anthesis in apricot and day 28 in apple.

Fruit set Percentage

Pollination treatment exerted a highly significant effect on fruit set percentage in both apricot and apple ($p<0.001$; Table 2). In apple, open-pollinated flowers recorded the highest mean fruit set at 72.4±4.2%, statistically superior ($p<0.001$) to both self-pollinated (18.3±2.7%) and hand cross-pollinated control

Table 1: Pollinator Community Composition, mean Visitation Metrics, and Pollinator Importance Values (PIV) for the ten dominant flower-visiting taxa recorded across apricot and apple orchards, Doda district, J&K (UT), 2023-2024.

Taxon (Order: Family)	% Visits	Visit Freq. ($fl^{-1} h^{-1}$)	Duration (s)	Contact Eff.	PIV	Apple (%)	Apricot (%)	Both (%)
Apis mellifera L. (Hym: *Apidae*)	41.2	6.8± 0.9	8.4±1.1	0.82	0.338	43.1	38.9	41.2
Apis cerana F. (Hym: *Apidae*)	28.6	5.3±0.7	9.2±1.3	0.85	0.243	29.4	27.6	28.6
Andrena spp. (Hym: *Andrenidae*)	6.4	2.1±0.5	12.6±2.1	0.91	0.058	7.2	5.8	6.4
Osmia spp. (Hym: *Megachilidae*)	5.1	1.8±0.4	14.3±2.4	0.94	0.048	4.8	5.4	5.1
Bombus spp. (Hym: *Apidae*)	3.2	0.8±0.2	10.1±1.8	0.87	0.028	2.1	4.3	3.2
Halictus spp. (Hym: *Halictidae*)	2.4	0.9±0.2	7.8±1.4	0.78	0.019	3.3	1.6	2.4
Lasioglossum spp. (Hym: *Halictidae*)	1.4	0.5±0.1	6.2±1.1	0.72	0.010	1.5	1.3	1.4
Xylocopa spp. (Hym: *Apidae*)	1.8	0.4±0.1	11.4±2.0	0.83	0.015	1.7	1.9	1.8
Episyrphus balteatus De Geer (Dip: *Syrphidae*)	5.2	1.2±0.3	4.1±0.8	0.38	0.020	5.1	5.3	5.2
Eristalis tenax L. (Dip: *Syrphidae*)	3.2	0.7±0.2	3.6±0.7	0.32	0.010	3.3	3.1	3.2

Table 2: Mean Fruit Set Percentage (± SE) across Pollination Treatments in Apple and Apricot Orchards, Doda district, J&K (UT), 2023-2024 (*n*= 320-340 Flowers per Treatment per site).

Pollination Treatment	Apple- Fruit Set (%)	Apricot- Fruit Set (%)	Significance (*p*)
Open Pollination (OP)	72.4±4.2 a	64.7±5.1 a	<0.001
Self-Pollination (SP)	18.3±2.7 b	21.6±3.3 b	<0.001
Hand Cross-Pollination (CP)	67.8±3.9 a	61.2±4.4 a	0.32 (vs. OP)

(67.8±3.9%) treatments (Tukey HSD). The fruit set reduction attributable to insect exclusion was large in both crops (Cohen's d=2.84 for apple; d=1.97 for apricot). In apricot, open-pollinated flowers achieved 64.7±5.1% fruit set compared to 21.6±3.3% in mechanically excluded self-pollinated flowers ($p<0.001$). The minimal and statistically non-significant difference between open-pollinated and hand cross-pollinated treatments in apple ($p=0.32$) confirms that ambient insect pollinator communities in Doda orchards delivered cross-pollination services functionally equivalent in efficiency to manual pollen transfer. Neither crop season (year) nor the year × treatment interaction exerted a statistically significant effect on fruit set percentage (all $p>0.20$). Orchard site contributed minor but significant random variance (σ^2_{site}=0.11-0.14).

Physicochemical Fruit Quality Parameters

Fruits from open-pollinated flowers exhibited superior physicochemical quality across nearly all measured parameters compared to mechanically excluded self-pollinated fruits in both crops (Table 3). Mean fruit weight under open pollination was 168.4±8.7 g in apple and 42.8±3.1 g in apricot, significantly exceeding self-pollinated values of 112.3± 6.2 g and 27.4±2.3 g, respectively ($p<0.01$). Seed content per fruit was significantly higher in open-pollinated apples (8.2±0.6 seeds per fruit vs. 2.4±0.4; $p<0.01$). TSS was significantly elevated in open-pollinated fruits (apple: 13.4±0.4 °Brix vs. 11.2±0.5 °Brix; apricot: 14.7±0.6 °Brix vs. 12.1±0.4 °Brix; $p<0.05$). Titratable acidity in apple did not differ significantly between OP and SP treatments (0.38 ± 0.02% vs. 0.42±0.03%; $p=0.18$), whereas apricot TA was significantly higher in self-pollinated fruits (1.51± 0.10% vs. 1.24± 0.08%; $p<0.05$). Ascorbic acid content was significantly higher in open-pollinated apricots (7.84± 0.62 vs. 5.23±0.48 mg/100 g FW; $p<0.05$). Pearson correlation analysis revealed significant positive correlations between pollinator visitation frequency and fruit weight (r=0.74, $p<0.001$), TSS (r=0.68, $p<0.001$), fruit set percentage (r=0.82, $p<0.001$), and seed number per fruit (r=0.77,

Table 3: Mean Physicochemical Quality Parameters (± SE) of Apple and Apricot Fruits under open Pollination (OP) and Self-Pollination under mechanical exclusion (SP), Doda district, J&K (UT), 2023-2024.

Parameter	Apple OP	Apple SP	Apricot OP	Apricot SP
Fruit Weight (g)	168.4±8.7*	112.3±6.2	42.8±3.1*	27.4±2.3
Fruit Volume (cm³)	182.6±9.4*	124.7±7.1	48.3±3.7*	31.6±2.8
TSS (°Brix)	13.4±0.4*	11.2±0.5	14.7±0.6*	12.1±0.4
Titratable Acidity (% malic acid)	0.38±0.02 ns	0.42±0.03	1.24±0.08*	1.51±0.10
TSS:TA Ratio	35.3±1.8*	26.7±1.4	11.9±0.7*	8.0±0.6
Ascorbic Acid (mg/100 g FW)	6.12±0.41*	4.27±0.35	7.84±0.62*	5.23±0.48
Seed Number per Fruit	8.2±0.6*	2.4±0.4	1.0±0.0*	0.4±0.1
Colour L* (Lightness)	62.3±1.4*	54.7±1.8	66.2±2.1*	58.4±1.9

$p<0.001$). Year had no significant effect on any physicochemical parameter (all $p>0.05$).

DISCUSSION

The results of this investigation furnish the first empirically grounded, treatment-controlled demonstration of insect pollinator impact on fruit set and physicochemical quality of apricot and apple in the Doda district of J&K (UT). The magnitude of fruit set reduction under insect exclusion exceeding 54 percentage points in apple (Cohen's d=2.84) and 43 percentage points in apricot (Cohen's d=1.97) is congruent with pollinator exclusion effect sizes reported in Kashmir Valley orchards (Abrol *et al.*, 2019) and in European apple-growing regions (Garratt *et al.*, 2014), reinforcing the generalizability of entomophily-dependency in *Malus domestica* across its pan-Eurasian cultivation range.

The predominance of *Apis mellifera* and *Apis cerana* as primary pollinators is consistent with their established status as principal managed pollinators in J&K horticultural systems. *Apis cerana*, native to the Indian subcontinent, demonstrated particular foraging activity at lower ambient temperatures, sustaining visits at approximately 38% of non-frost-day frequencies during frost events when *Apis mellifera* foraging was completely suppressed. This thermoregulatory advantage may confer a critical pollination benefit during the early-spring thermal instability of Doda's higher-elevation orchards, aligning with the thermoregulatory ecology documented by Abrol *et al*. (2019). The contribution of solitary bee taxa, particularly *Osmia* spp. (PIV=0.048) and *Andrena* spp. (PIV=0.058), though numerically smaller in terms of visit frequency, should not be discounted; their substantially higher stigmatic contact efficiency (0.91-0.94) implies ecological impact exceeding that predicted by visit frequency data alone (Bosch and Kemp, 2002).

The observed quality differentials between open-pollinated and self-pollinated fruits are mechanistically interpretable through the role of seed content as an auxin and gibberellin source during fruit development (Hancock *et al*., 2015). The strong positive correlation between visitation frequency and seed number per fruit (r=0.77, $p<0.001$) constitutes mechanistically explicit evidence linking insect pollinator activity to downstream fruit quality through the seed-hormone pathway. The non-significant effect of pollination treatment on apple titratable acidity is biologically explicable, as organic acid metabolism in apple is governed predominantly by post-harvest enzymatic catabolism driven by cultivar-specific malic enzyme activity and storage temperature, operating independently of seed content (Ferree and Warrington, 2003). The absence of a significant year effect on fruit set and physicochemical parameters strengthens the temporal generalizability of the reported treatment differences. The phenological data flowering cessation in apricot by day 22 and in apple by day 28 post-anthesis establish a precise temporal window directly applicable to hive introduction scheduling and pesticide moratorium implementation by growers in Doda district.

CONCLUSION

These findings collectively support the hypothesis that insect pollinators make a quantifiable, irreplaceable contribution to the yield and physicochemical quality of both apricot and apple in Doda district. Future research should investigate the economic valuation of pollination services in monetary terms (market price × yield differential per hectare), expand the study to additional cultivars and agro-ecological zones within J&K (UT), and examine the impact of landscape-scale habitat management on solitary bee community diversity and pollination reliability over multi-year horizons.

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ABBREVIATIONS

OP: Open Pollination; **SP:** Self-Pollination; **CP:** Hand Cross-Pollination; **PIV:** Pollinator Importance Value; **TSS:** Total Soluble Solids; **TA:** Titratable Acidity; **FW:** Fresh Weight; **BBCH:** Biologische Bundesanstalt, Bundessortenamt and Chemical Industry growth scale; **ANOVA:** Analysis of Variance; **HSD:** Honestly Significant Difference; **GLMM:** Generalized Linear Mixed Model; **lmer():** Linear Mixed-Effects Regression Function; **ºC:** Degrees Celsius; **m s^{-1}:** Metres per Second; **UT:** Union Territory; **CIE:** Commission Internationale de l'Éclairage; **mm:** Millimetres; **h:** Hours; **%**: Percentage; **vs:** Versus; **cv:** Cultivar; **spp:** Multiple Species within a Genus; **sp:** Single Unidentified Species within a Genus; **L:** Linnaeus; **F:** Fabricius; **J&K:** Jammu and Kashmir.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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AUTHOR CONTRIBUTIONS

Rohit Rohit: Conceptualization, Methodology, Formal analysis and investigation, Writing-original draft, Writing-review and editing, Data curation, Visualization, Project administration. Anjali Dhar: Conceptualization, Methodology, Validation, Resources, Writing-review and editing, Supervision.

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