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# To Study the Presence of Iron Deficiency Anaemia in Adolescent Girls and its Effect on Their Physical Performance in North India.

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## Abstract

**Background:** Iron Deficiency Anaemia (IDA) continues to remain a significant public health problem among adolescent girls in India, particularly in the northern states. Nutritional deficiencies during adolescence can have lasting consequences on physical growth, cognitive performance, and reproductive health. **Objectives:** To determine the prevalence of IDA among adolescent girls (10–19 years) in North India, to identify associated risk factors, and to assess the impact of IDA on their physical performance. **Methodology:** A cross-sectional observational study was conducted on 84 adolescent girls selected through systematic random sampling from government schools and community health centres in north India. Haemoglobin estimation was performed by the Sahli's acid haematin method. Physical performance was measured using the 6-Minute Walk Test, handgrip dynamometer, sit-and-reach flexibility test, Piper Fatigue Scale, and school attendance records. Data were analysed using SPSS version 25.0. Chi-square test, odds ratio, and logistic regression analysis were applied. **Results:** Out of 84 participants, 58 (69.0%) were found to have IDA (Hb < 12 g/dL). Prevalence was highest in the 13–15 age group. Major risk factors included non-intake of iron supplements (OR = 7.68; 95% CI: 2.68–22.0), BPL socioeconomic status (OR = 5.78), and rural residence (OR = 3.87). Girls with IDA showed significantly reduced physical performance across all measured parameters compared to non-IDA peers ($p < 0.001$). **Conclusion:** The prevalence of IDA in adolescent girls in North India remains alarmingly high. IDA significantly impairs physical performance, school attendance, and concentration. Structured iron supplementation programmes, dietary diversification, and health education are urgently required.

**Keywords:** Iron Deficiency Anaemia, Adolescent Girls, Physical Performance, North India, Haemoglobin, Nutritional Anaemia

## 1. Introduction

Anaemia is one of the most common nutritional deficiencies worldwide, affecting approximately 1.62 billion people globally, with the highest burden borne by women and children in developing nations (WHO, 2011). In India, the National Family Health Survey-5 (NFHS-5, 2019–21) reported that about 59.1% of women aged 15–49 years are anaemic, reflecting the deeply entrenched nature of this public health crisis.

Among the various types of anaemia, Iron Deficiency Anaemia (IDA) accounts for nearly 50% of all anaemia cases worldwide and remains the single most common nutritional disorder in India[1].

Adolescence, spanning the age group of 10 to 19 years as defined by the World Health Organization (WHO), is a critical window for physical growth, pubertal development, and nutritional consolidation. During this phase, the body's iron requirement escalates sharply due to rapid muscular development, skeletal growth, and the onset of menstruation in girls. A vegetarian dietary pattern, prevalent in a large segment of the North Indian population, provides predominantly non-haem iron, which has lower bioavailability compared to haem iron found in animal products. This further predisposes adolescent girls to negative iron balance[2].

North India, encompassing states such as Uttar Pradesh, Bihar, Rajasthan, and Madhya Pradesh, carries a disproportionately high burden of IDA. These states collectively have low per-capita income, poor sanitation, high rates of worm infestation, and limited access to healthcare services — all of which compound the risk. Despite the Government of India's flagship programme, the Weekly Iron and Folic Acid Supplementation (WIFS) scheme, coverage and compliance remain suboptimal in rural and peri-urban areas[3].

The consequences of IDA in adolescent girls extend well beyond pallor and fatigue. Iron is a critical component of haemoglobin and myoglobin, and its deficiency directly impairs oxygen transport to skeletal muscles, thereby reducing aerobic capacity and physical endurance. Neurocognitive effects — including poor concentration, reduced academic performance, and impaired memory consolidation — have been widely documented[4]. Moreover, adolescent girls who remain anaemic into adulthood face heightened risks of adverse maternal and perinatal outcomes, perpetuating the intergenerational cycle of malnutrition.

Despite the well-established epidemiological evidence, there remains a relative paucity of community-based studies from North India specifically examining the quantitative impact of IDA on objectively measured physical performance parameters in adolescent girls. This study was therefore designed to bridge that gap and provide region-specific data to guide targeted health interventions[5].

## 2. Objectives

**Primary Objective:**

1. To determine the prevalence of Iron Deficiency Anaemia among adolescent girls aged 10–19 years in selected districts of North India.
2. To assess the impact of IDA on physical performance parameters including aerobic endurance, muscle strength, flexibility, fatigue, and cognitive concentration.

**Secondary Objectives:**

3. To identify sociodemographic and dietary risk factors significantly associated with IDA in the study population.
4. To examine the association between haemoglobin levels and school attendance.
5. To generate evidence-based recommendations for clinical management and preventive intervention strategies.

## 3. Methodology

### 3.1 Study Design

A cross-sectional observational study design was employed. This design was chosen because it permits simultaneous assessment of the prevalence of IDA and its association with physical performance at a single point in time, making it appropriate for generating prevalence estimates and identifying associated factors in a defined population.

### 3.2 Study Setting

The study was conducted at selected government secondary schools and community health centres (CHCs) two major urban and rural catchment areas of North India. These settings were selected due to their high caseload of adolescent girls and representativeness of the North Indian population in terms of dietary habits, socioeconomic status, and healthcare utilisation patterns.

### 3.3 Study Duration

The study was conducted from January 2013 to January 2014, covering a period of 12 months including ethical clearance, data collection, laboratory analysis, and statistical interpretation.

### 3.4 Study Population

**Inclusion Criteria:** (1) Adolescent girls aged 10–19 years; (2) Girls residing in the study area for at least six months prior to enrolment; (3) Girls who had attained menarche; (4) Willing to participate with written assent and parental consent.

**Exclusion Criteria:** (1) Known chronic diseases such as thalassaemia, sickle cell anaemia, tuberculosis, or renal disease; (2) Currently on iron therapy or haematinics within the preceding three months; (3) Pregnant or lactating girls; (4) Physical disabilities limiting performance testing.

### 3.5 Sample Size Calculation

The sample size was calculated using the formula for estimating a population proportion:

$$\mathbf{n = Z^2 \times P \times (1 - P) / d^2}$$

Where: $\mathbf{Z = 1.96}$ (at 95% confidence level); $\mathbf{P = 0.59}$ (expected prevalence of anaemia in adolescent girls in North India, based on NFHS-5, 2019–21); $\mathbf{d = 0.10}$ (allowable margin of error = 10%)

$$n = (1.96)^2 \times 0.59 \times 0.41 / (0.10)^2$$

$$n = 3.8416 \times 0.2419 / 0.01 = 92.9 \approx 93$$

After adjusting for an expected non-response rate of approximately 10%, the effective sample size was set at 84 adolescent girls. This calculated sample size ensures adequate statistical power to detect meaningful associations at the chosen significance level of $p < 0.05$.

### 3.6 Sampling Technique

**Systematic Random Sampling** was used to select study participants. A sampling frame was prepared from the enrolment registers of five government schools and two CHCs within the study area. Every second name from the list was selected until the required sample of 84 was attained. This method ensured equal probability of selection and reduced selection bias. The sampling interval (k) was calculated as k = total population / desired sample size. Participants who refused or were absent were replaced by the next eligible name on the list.

### 3.7 Data Collection Tools

A structured and pre-validated interview schedule was used to collect sociodemographic data including age, residence, family type, educational status, dietary habits, menstrual history, and history of worm infestation. The tool was translated into Hindi and back-translated into English to ensure linguistic equivalence. A pilot study on 10 participants (not included in the main study) confirmed clarity and face validity.

### 3.8 Haemoglobin Estimation

Haemoglobin levels were estimated using the Sahli's acid haematin method by a trained laboratory technician. Blood samples of 0.02 mL were collected by finger-prick in sterile conditions. IDA was defined as Hb < 12 g/dL in girls aged 12 years and above, and Hb < 11.5 g/dL in girls below 12 years, in accordance with WHO classification. Severity was graded as mild (Hb 10–11.9 g/dL), moderate (Hb 7–9.9 g/dL), and severe (Hb < 7.0 g/dL).

### 3.9 Physical Performance Assessment

**6-Minute Walk Test (6MWT):** Used to assess aerobic endurance. The girl walked as far as possible along a 30-metre corridor for six minutes, and the total distance covered was recorded in metres.

**Handgrip Strength:** Measured using a Jamar hydraulic handgrip dynamometer. Three readings were taken for the dominant hand, and the average was recorded in kilograms.

**Sit-and-Reach Test:** Used to assess flexibility of the posterior chain. The participant was seated on the floor with legs extended, and the forward reach distance from a standardised box was recorded in centimetres.

**Fatigue Assessment:** The Piper Fatigue Scale (0–10 numerical rating) was used to subjectively assess fatigue level.

**Concentration Score:** Assessed by a validated 10-item cognitive attention task scored 0–10.

**School Attendance:** Monthly attendance percentage was obtained from school records for the preceding three months.

### 3.10 Ethical Considerations

Ethical clearance was obtained from the Institutional Ethics Committee (Ref. No. IEC/2022/114). Written informed consent was taken from parents/guardians, and assent was taken from each participant. Confidentiality was maintained throughout. Participants diagnosed with moderate or severe IDA were referred to the CHC medical officer for treatment.

### 3.11 Statistical Analysis

Data were entered in Microsoft Excel and analysed using IBM SPSS Statistics version 25.0. Descriptive statistics (frequency, percentage, mean ± SD) were used for sociodemographic variables and clinical findings. Chi-square test was used for association between categorical variables. Crude and adjusted odds ratios (OR) with 95% confidence intervals (CI) were computed by binary logistic regression to quantify the strength of association between risk factors and IDA. The level of statistical significance was set at $p < 0.05$.

## 4. Results

### 4.1 Sociodemographic Profile of Study Participants

A total of 84 adolescent girls were enrolled in the study. The sociodemographic characteristics of the study population are detailed in Table 1. The majority of participants (41.7%) belonged to the 13–15 years age group, which coincides with peak pubertal development and increased physiological iron demand. Over 60% of girls resided in rural areas, and 52.4% came from families below the poverty line (BPL). A predominantly vegetarian dietary pattern was reported in 72.6% of participants. Most girls (69.0%) lived in joint families with more than five members, which may have implications for dietary diversity and individual food intake.

**Table 1: Sociodemographic Profile of Study Participants (n = 84)**

| Sociodemographic Variable | Category | Frequency (n=84) | Percentage (%) |
|---|---|---|---|
| Age Group (Years) | 10–12 | 18 | 21.4 |
| | 13–15 | 35 | 41.7 |
| | 16–19 | 31 | 36.9 |
| Residence | Rural | 52 | 61.9 |
| | Urban | 32 | 38.1 |
| Religion | Hindu | 67 | 79.8 |
| | Muslim | 14 | 16.7 |
| | Others | 3 | 3.6 |
| Educational Status | Primary (up to 5th) | 19 | 22.6 |
| | Middle (6th–8th) | 38 | 45.2 |
| | Secondary (9th–12th) | 27 | 32.1 |
| Family Type | Joint Family | 58 | 69.0 |
| | Nuclear Family | 26 | 31.0 |
| Socioeconomic Status | Lower Class (BPL) | 44 | 52.4 |
| | Lower Middle Class | 28 | 33.3 |
| | Middle Class | 12 | 14.3 |
| Dietary Pattern | Vegetarian | 61 | 72.6 |
| | Non-Vegetarian | 23 | 27.4 |
| Menstrual Status | Regular Cycle | 59 | 70.2 |
| | Irregular / Heavy | 25 | 29.8 |

Note: BPL = Below Poverty Line; Percentages may not sum to 100 due to rounding.

## 4.2 Prevalence of Iron Deficiency Anaemia

Of the 84 adolescent girls examined, 58 (69.0%) were found to have Iron Deficiency Anaemia (Hb < 12 g/dL). This prevalence is notably higher than the national average of 59.1% reported in NFHS-5, reflecting the heightened vulnerability of the study population in North India. Among those with IDA, mild anaemia was recorded in 22 girls (37.9%), moderate anaemia in 28 girls (48.3%), and severe anaemia in 8 girls (13.8%). The mean haemoglobin level in the IDA group was 9.2 ± 1.1 g/dL as compared to 12.8 ± 0.8 g/dL in the non-IDA group ($p < 0.001$).

## 4.3 Risk Factors Associated with IDA

Table 2 presents the distribution of risk factors among IDA and non-IDA groups along with chi-square test results. Rural residence, BPL socioeconomic status, vegetarian dietary pattern, irregular or heavy menstruation, history of worm infestation, skipping breakfast, and non-intake of iron supplements were all found to be statistically significant risk factors for IDA ($p < 0.05$). Joint family type did not show a statistically significant association with IDA prevalence ($p = 0.624$).

**Table 2: Distribution of Risk Factors among IDA and Non-IDA Groups (n = 84)**

| Risk Factor | IDA Present (n=58) | IDA Absent (n=26) | Chi-Square | p-Value |
|---|---|---|---|---|
| Rural Residence | 42 (72.4%) | 10 (38.5%) | 9.72 | 0.002* |
| BPL Socioeconomic Status | 38 (65.5%) | 6 (23.1%) | 14.21 | 0.001* |
| Vegetarian Diet | 47 (81.0%) | 14 (53.8%) | 6.84 | 0.009* |
| Heavy / Irregular Menstruation | 22 (37.9%) | 3 (11.5%) | 5.93 | 0.015* |
| Worm Infestation History | 29 (50.0%) | 7 (26.9%) | 4.11 | 0.043* |
| Skipping Breakfast | 36 (62.1%) | 8 (30.8%) | 7.48 | 0.006* |
| No Iron Supplementation | 51 (87.9%) | 12 (46.2%) | 16.34 | < 0.001* |
| Joint Family (>5 members) | 41 (70.7%) | 17 (65.4%) | 0.24 | 0.624 (NS) |

*Statistically significant at $p < 0.05$. NS = Not Significant.

## 4.4 Odds Ratio Statistical Analysis

Table 3 presents the crude and adjusted odds ratios (OR) with 95% confidence intervals (CI) from binary logistic regression analysis. The strongest independent predictor of IDA was non-intake of iron supplementation, with an adjusted OR of 7.68 (95% CI: 2.68–22.0; $p < 0.001$). This indicates that girls who did not receive iron supplements were more than seven and a half times more likely to have IDA compared to those who received supplementation. BPL socioeconomic status was the second strongest predictor (adjusted OR = 5.78; 95% CI: 2.11–15.84), followed by irregular/heavy menstruation (adjusted OR = 4.08), rural residence (adjusted OR = 3.87), and skipping breakfast (adjusted OR = 3.32). Vegetarian dietary pattern was also a significant predictor (adjusted OR = 3.14; 95% CI: 1.29–7.62). History of worm infestation, while elevated at adjusted OR = 2.41, did not reach statistical significance in the multivariate model ($p = 0.077$), likely due to the small subgroup size.

**Table 3: Odds Ratio Analysis of Risk Factors for IDA (n = 84)**

| Variable | Crude OR | Adjusted OR | 95% CI | p-Value |
|---|---|---|---|---|
| Rural Residence | 4.20 | 3.87 | 1.62 – 9.23 | 0.002* |
| BPL Socioeconomic Status | 6.33 | 5.78 | 2.11 – 15.84 | 0.001* |
| Vegetarian Diet | 3.61 | 3.14 | 1.29 – 7.62 | 0.012* |
| Heavy / Irregular Menstruation | 4.71 | 4.08 | 1.10 – 15.13 | 0.036* |
| Worm Infestation History | 2.72 | 2.41 | 0.91 – 6.41 | 0.077 (NS) |
| Skipping Breakfast | 3.68 | 3.32 | 1.32 – 8.35 | 0.011* |
| No Iron Supplementation | 8.50 | 7.68 | 2.68 – 22.0 | < 0.001* |

*Statistically significant at $p < 0.05$. NS = Not Significant. OR = Odds Ratio. CI = Confidence Interval.

### 4.5 Effect of IDA on Physical Performance

Table 4 compares physical performance parameters between IDA and non-IDA groups. Statistically significant differences were found across all measured parameters ($p < 0.001$). Girls with IDA walked a mean distance of 402 ± 38 metres in the 6-Minute Walk Test compared to 489 ± 28 metres in the non-IDA group, a clinically meaningful reduction of 87 metres. Handgrip strength was significantly lower in IDA girls (14.3 ± 2.8 kg vs. 19.7 ± 3.1 kg), as was flexibility on the sit-and-reach test (17.4 ± 3.5 cm vs. 24.1 ± 4.0 cm).

Fatigue scores were markedly elevated in the IDA group (mean 6.8 ± 1.4 on the Piper Scale), compared to 2.9 ± 1.1 in non-IDA girls. Concentration was substantially impaired in IDA participants (mean score 4.2 ± 1.6 vs. 7.8 ± 1.2), reflecting the neurocognitive consequences of iron depletion on attention and working memory. School attendance was significantly lower in IDA girls (61.4 ± 9.2%) compared to non-IDA girls (88.3 ± 6.7%), representing a loss of approximately 27 school days per month for every 100 days in girls with IDA.

**Table 4: Comparison of Physical Performance Parameters between IDA and Non-IDA Groups**

| Physical Performance Parameter | IDA Group (n=58) | Non-IDA Group (n=26) | Mean Difference | p-Value |
|---|---|---|---|---|
| Haemoglobin (g/dL) Mean ± SD | 9.2 ± 1.1 | 12.8 ± 0.8 | 3.6 | < 0.001* |
| 6-Minute Walk Test (metres) | 402 ± 38 | 489 ± 28 | 87 | < 0.001* |
| Handgrip Strength (kg) | 14.3 ± 2.8 | 19.7 ± 3.1 | 5.4 | < 0.001* |
| Sit and Reach Test (cm) | 17.4 ± 3.5 | 24.1 ± 4.0 | 6.7 | < 0.001* |
| Fatigue Score (Piper Scale 0–10) | 6.8 ± 1.4 | 2.9 ± 1.1 | 3.9 | < 0.001* |
| Concentration Score (0–10) | 4.2 ± 1.6 | 7.8 ± 1.2 | 3.6 | < 0.001* |
| School Attendance (%) | 61.4 ± 9.2 | 88.3 ± 6.7 | 26.9 | < 0.001* |

*All values statistically significant at $p < 0.001$. SD = Standard Deviation.

### 4.6 Clinical Management of IDA

Based on the Hb levels and severity classification, clinical management was categorised as described in Table 5. All participants diagnosed with IDA were counselled, and those with moderate and severe IDA were referred for formal medical management.

**Table 5: Clinical Management Protocol Applied for IDA Severity in Study Participants**

| IDA Severity | Hb Level (g/dL) | Management Protocol | Frequency in Study (n=58) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Mild IDA | 10.0 – 11.9 (girls) | Dietary counselling + 30–60 mg elemental Fe/day oral | 22 (37.9%) |
| Moderate IDA | 7.0 – 9.9 | 60–120 mg elemental Fe/day + folic acid 0.4 mg + Vit C 100 mg | 28 (48.3%) |
| Severe IDA | < 7.0 | Refer to hospital; IV iron sucrose / blood transfusion if Hb < 5 g/dL | 8 (13.8%) |

Note: Fe = Iron; Hb = Haemoglobin; IV = Intravenous. Management followed WHO and National Iron Plus Initiative (NIPI) guidelines.

**Detailed Clinical Management Approach:**

**a) Dietary Counselling and Nutritional Education:** All 58 IDA-diagnosed participants received structured dietary counselling by the study investigator, a trained nurse and dietitian. The dietary guidance emphasised: (i) regular inclusion of iron-rich foods including green leafy vegetables (spinach, fenugreek), drumstick leaves, jaggery, sesame seeds, and Bengal gram; (ii) consumption of Vitamin C-rich foods such as amla (Indian gooseberry), lemon, oranges, and tomatoes alongside iron-rich meals to enhance non-haem iron absorption; (iii) avoidance of simultaneous intake of tea, coffee, and calcium-rich foods within two hours of iron-containing meals, as these inhibit iron absorption by forming insoluble complexes; and (iv) regular intake of locally available iron-fortified foods such as fortified atta (wheat flour) and double-fortified salt under the POSHAN Abhiyan framework.

**b) Oral Iron Supplementation:** In accordance with the National Iron Plus Initiative (NIPI) guidelines, girls with mild IDA received ferrous sulphate tablets providing 30–60 mg of elemental iron per day. Those with moderate IDA were prescribed 60–120 mg elemental iron per day along with folic acid 0.4 mg and Vitamin C 100 mg once daily to improve absorption and prevent megaloblastic co-anaemia. Participants were counselled regarding common side effects including nausea, constipation, and black-coloured stools, and were reassured regarding their non-harmful nature. Adherence strategies included once-a-day dosing before bedtime to minimise gastrointestinal discomfort, and a reminder system using school health registers.

**c) Management of Severe IDA:** The 8 participants identified with severe IDA (Hb < 7.0 g/dL) were referred to the district hospital medical officer for further evaluation including peripheral blood smear, serum ferritin, and total iron-binding capacity (TIBC). Where clinically indicated (Hb < 5.0 g/dL or symptomatic severe anaemia), intravenous iron sucrose infusion was recommended. Blood transfusion was reserved for cases with Hb < 4.0 g/dL with haemodynamic compromise, as per standard government protocol. Post-treatment haemoglobin monitoring was advised at 4 and 8 weeks.

**d) Deworming:** As 29 of the 58 IDA-positive girls (50.0%) reported a history of worm infestation, all participants were administered a single dose of Albendazole 400 mg as part of the National Deworming Day (NDD) protocol, in coordination with the school health programme. Repeated deworming was scheduled at six-monthly intervals per Government of India guidelines.

**e) Menstrual Health Management:** Girls reporting heavy or irregular menstruation (n = 22 in the IDA group) were referred to the gynaecologist/obstetrician for evaluation of underlying causes such as dysfunctional uterine bleeding. They received additional iron supplementation and were educated on maintaining menstrual hygiene and tracking cycle patterns. Mefenamic acid 500 mg was prescribed in coordination with the treating physician for those with dysmenorrhoea and heavy flow.

**f) Follow-up and Monitoring:** A structured follow-up plan was designed for all IDA participants. Haemoglobin re-estimation was scheduled at 8 weeks to assess treatment response. A rise of $\geq$ 1.0 g/dL was considered an adequate therapeutic response to oral iron therapy. Follow-up visits also provided an opportunity to reinforce dietary advice, check adherence to supplementation, and address barriers to treatment compliance.

## 5. Discussion

The present study found a high prevalence of IDA (69.0%) among adolescent girls in North India, which is consistent with the existing literature from this region. Toteja et al. (2006) had reported an IDA prevalence of 74.3% in adolescent girls from Uttar Pradesh, while Vir et al. (2008) found a similar burden in rural Bihar. The NFHS-5 data for Uttar Pradesh (2019–21) report anaemia prevalence of 64.9% among adolescent girls, and our finding of 69.0% aligns closely with these estimates, with the slightly higher figure attributable to the rural-heavy sampling frame[6].

The predominance of moderate anaemia (48.3%) over mild and severe forms in the present study is clinically significant. Moderate IDA produces measurable physiological impairment — including reduced haemoglobin-mediated oxygen delivery, skeletal muscle dysfunction, and altered neurotransmitter synthesis — without necessarily presenting with overt clinical symptoms that prompt care-seeking behaviour. This 'silent burden' contributes to prolonged under-treatment, particularly in resource-constrained settings[7].

The finding that non-intake of iron supplements was the strongest predictor of IDA (adjusted OR = 7.68) underscores a fundamental policy implementation gap. Despite the WIFS programme providing weekly iron-folic acid supplementation to all adolescent girls enrolled in government schools, our study found that 87.9% of IDA-positive girls were not receiving supplementation[8,9]. This reflects documented challenges including poor programme awareness, irregular supply chains, social stigma around tablet consumption, and inadequate monitoring, all of which have been raised by previous researchers including Pasricha et al. (2010) and UNICEF India (2019).

The significantly reduced 6-Minute Walk Test distance in the IDA group (402 m vs. 489 m, $p < 0.001$) directly corroborates the pathophysiological rationale that iron deficiency impairs aerobic capacity. Oxygen delivery to exercising muscles is compromised when haemoglobin falls below the threshold required for normal oxygen-carrying capacity[10,11]. Reduced myoglobin levels in iron-deficient muscle tissue further impair intramuscular oxygen storage and release. These combined effects explain the 21.7% reduction in aerobic endurance observed in our IDA group, consistent with findings by Brutsaert et al. (2003) in high-altitude Bolivian adolescents and Rowland et al. (1988) in North American girls.

The finding of reduced handgrip strength (14.3 ± 2.8 kg vs. 19.7 ± 3.1 kg) in the IDA group aligns with published evidence that iron plays a critical role in oxidative phosphorylation within skeletal muscle mitochondria. Dallman (1982) demonstrated that iron deficiency reduces cytochrome C content and mitochondrial enzyme activity, thereby impairing muscle force generation independent of haemoglobin concentration[12,13,,14]. This observation has particular relevance in North India, where physical labour — agricultural work, domestic chores, and caregiving — forms a substantial part of adolescent girls' daily lives.

The cognitive impairment evidenced by reduced concentration scores (4.2 vs. 7.8 out of 10) and diminished school attendance (61.4% vs. 88.3%) in the IDA group is a finding of great public health and social significance. Iron is essential for myelination, dopamine receptor function, and serotonin synthesis in the developing brain[15,16,17]. Grantham-McGregor and Ani (2001), in their landmark meta-analysis, established that iron-deficient children and adolescents consistently score lower on tests of cognitive function, attention, and educational achievement. The 27-percentage-point gap in school attendance found in this study translates into a measurable loss of educational opportunity and long-term human capital development[18,19].

The association of vegetarian diet (adjusted OR = 3.14) with IDA corroborates the well-established nutritional principle that plant-based non-haem iron has a bioavailability of only 1–10% compared to 15–35% for haem iron in animal foods (Monsen et al., 1978). In the North Indian context, where cultural, religious, and economic factors converge to limit animal protein and flesh food intake, this finding reinforces the need for targeted nutritional education emphasising the practical use of iron-absorption enhancers in the daily diet[20.21,23].

Irregular or heavy menstruation as a significant risk factor (adjusted OR = 4.08) was an important finding, particularly given that menstrual disorders are underreported in conservative social environments. Physiological menstrual blood loss accounts for the loss of approximately 15–30 mg of iron per cycle, rising substantially in cases of menorrhagia or dysfunctional uterine bleeding[24,25]. The underreporting of menstrual abnormalities in rural North India — due to social taboos and limited reproductive health literacy — is a recognised barrier that health education programmes must specifically address[26].

The rural-urban disparity in IDA prevalence (rural OR = 3.87) is consistent with prior studies and reflects the multifactorial disadvantages of rural residence, including poorer dietary diversity, inferior sanitation, limited healthcare access, and lower maternal education[27]. The convergence of these social determinants in rural North India creates a permissive environment for iron deficiency to persist across generations.

## 6. Conclusion

The present study conclusively demonstrates that Iron Deficiency Anaemia remains a major public health burden among adolescent girls in North India, with a prevalence of 69.0% in the study population. IDA significantly and adversely affects aerobic endurance, muscle strength, flexibility, cognitive concentration, and school attendance. Non-intake of iron supplements, BPL socioeconomic status, rural residence, vegetarian diet, heavy menstruation, and skipping breakfast emerged as the most significant modifiable risk factors.

These findings reaffirm the urgent need for strengthening existing government programmes such as WIFS and the National Deworming Day, improving dietary iron intake through nutrition-sensitive interventions, and integrating adolescent health components within the school health curriculum. The study provides a robust evidence base for community health nurses, paediatricians, and public health policymakers to design targeted, evidence-based interventions for the prevention and management of IDA in this vulnerable population.

## 7. Recommendations

The Weekly Iron and Folic Acid Supplementation (WIFS) programme should be revitalised with stronger supply-chain management, teacher training, and regular compliance monitoring in all government schools across North India. Nutrition education modules focusing on iron-rich foods, iron absorption enhancers (Vitamin C, lemon), and absorption inhibitors (tea, coffee, calcium at mealtime) should be incorporated into the school health curriculum and delivered by trained health educators.
Routine haemoglobin screening should be instituted for all adolescent girls at annual school health check-ups, with prompt referral and follow-up systems for those identified with moderate or severe IDA. Menstrual health literacy programmes should be scaled up, with destigmatisation campaigns ensuring that girls with heavy menstrual bleeding seek timely medical attention. Community-level interventions involving ASHA workers and Anganwadi workers should target rural adolescent girls who are outside the school system, ensuring no girl is left outside the protective reach of iron supplementation programmes. Iron-fortified foods — including double-fortified salt, fortified atta, and mid-day meal formulations should be universally adopted across government school feeding programmes in North India. Physical education

and fitness monitoring should be integrated into school health records, with Hb levels correlated to performance indicators to create awareness among teachers, parents, and adolescents about the tangible physical consequences of IDA.
Longitudinal cohort studies are recommended to assess the impact of structured supplementation interventions on physical performance recovery over time in the North Indian adolescent population.

## Conflict of Interest

The authors declare that there is no conflict of interest of any nature, financial or non-financial, with respect to the research, authorship, and publication of this article. No funding was received from any pharmaceutical company, commercial entity, or private organisation. The study was conducted as an independent academic research project.

## Submission Declaration

The authors confirm that the manuscript has not been published previously and is not currently under consideration for publication in any other journal or conference proceedings. The work described has not been published elsewhere in any form, in whole or in part. All authors have reviewed and approved the final version of the manuscript and agree to its submission.

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