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ORIGINAL ARTICLE

Re-Emergence of Thiamine Deficiency Among Pregnant and Lactating Women in Northeast India

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ABSTRACT

Thiamine (vitamin B1) deficiency, once considered controlled in India, has re-emerged in parts of Northeast India, raising concern for maternal and infant health. We conducted a community-based cross-sectional study during 2023–2024 to estimate its prevalence and dietary determinants among pregnant and lactating women in the Barak Valley of Assam and adjoining districts of Tripura. Using multistage cluster sampling, women were recruited from 120 villages with documented beriberi clusters. Thiamine status was assessed by determining the erythrocyte transketolase activation coefficient (ETKAC), a functional marker, and whole-blood thiamine diphosphate (ThDP), a biochemical marker measured by high-performance liquid chromatography. Of 1329 women, 1083 were analyzed. Both markers gave similar estimates of suboptimal status: 20.1% by ThDP (95% CI: 17.8–22.6; deficient: 4.9%, marginal: 15.2%) and 20.6% by ETKAC (95% CI: 18.3–23.1; severe: 8.5%, marginal: 12.1%), higher among pregnant than lactating women. Diets were rice-based with low diversity. As the functional marker ETKAC was more sensitive to dietary context, we focused on its determinants: stored rice, washing rice repeatedly before cooking, and drinking salted tea were each associated with higher odds of ETKAC-defined suboptimal status. Socioeconomic disadvantage further increased risk. This substantial, subclinical, preventable burden driven by dietary monotony and thiamine-depleting rice practices underscores the need for targeted maternal nutrition strategies.

1 | Introduction

Thiamine (vitamin B1) is an essential water-soluble micronutrient required for carbohydrate metabolism and normal neuronal function. Because body stores are limited and turnover is rapid, a continuous dietary supply is necessary. Diets dominated by refined carbohydrates, particularly polished rice, predispose to thiamine deficiency disorders (TDDs), which include wet and dry beriberi and Wernicke–Korsakoff syndrome. Clinical progression can be rapid, and delayed diagnosis or treatment may result in substantial morbidity and mortality. Thiamine deficiency, therefore, remains a significant public health concern in low-resource, rice-dependent populations [1, 2].

Globally, thiamine deficiency remains an ongoing public health challenge in parts of South and Southeast Asia, with recurrent

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outbreaks reported in Laos [3], Cambodia [4], Thailand [5], Myanmar, and Bangladesh [1]. In India, recent evidence indicates the re-emergence of thiamine deficiency in specific geographic pockets, including Jammu and Kashmir [6] and the northeastern states [7], where rice-based diets and limited dietary diversity persist. Historically, TDDs have been widespread, especially among populations consuming polished rice due to thiamine loss during milling and polishing. Although dietary diversification and nutrition programs have reduced the overall burden, endemic pockets and outbreaks continue to occur among socioeconomically vulnerable groups that consume monotonous, carbohydrate-dense diets. Additional risk factors include food preparation practices that discard cooking water and the consumption of thiaminase-containing or thiamine-inhibitory foods. Pregnant and lactating women are particularly vulnerable because of increased physiological requirements; maternal deficiency directly reduces breastmilk thiamine content, placing exclusively breastfed infants at high risk of rapidly fatal infantile beriberi [8] if unrecognized.

In Northeast India, particularly the Barak Valley region of southern Assam and the adjoining districts of Tripura, reports of suspected thiamine deficiency and beriberi among women and infants have raised significant public health concerns. This region is characterized by widespread consumption of polished rice as the staple food, low dietary diversity with infrequent intake of thiamine-rich foods such as pulses and animal-source foods, and traditional rice preparation methods involving repeated washing and discarding of cooking water, all of which substantially reduce thiamine content [2, 7]. In addition, our internal field research indicates that localized gaps in maternal and child health and nutrition services, including limited coverage of Anganwadi services in some communities, may further increase vulnerability among pregnant and lactating women and infants. Hospital-based case series and outbreak investigations have documented clusters of infantile and adult beriberi [9], linking these presentations to these dietary and contextual risk factors. Assessments by the ICMR–National Institute of Nutrition have further identified suspected beriberi-related infant deaths in the region and reported these findings to the Ministry of Health and Family Welfare, underscoring the need for systematic population-level investigation. Notably, most prior evidence from the region has relied on clinical diagnosis and therapeutic response to thiamine, as laboratory-based assessment of thiamine status such as erythrocyte transketolase activation coefficient (ETKAC) or thiamine diphosphate (ThDP) measurements through high-performance liquid chromatography (HPLC) method has historically been unavailable.

Despite accumulating clinical and programmatic signals, community-based data on the prevalence and determinants of thiamine deficiency among high-risk populations in Northeast India remain scarce. In settings where underdiagnosis and unrecognized beriberi-related mortality are plausible, estimating the community-level burden is essential for prioritizing targeted public health interventions rather than for broad population generalization. Pregnant and lactating women represent a critical group for such assessment given their vulnerability and the intergenerational consequences of deficiency.

Therefore, this study aimed to estimate the prevalence of thiamine deficiency among pregnant and lactating women residing in selected high-risk districts of the Barak Valley of Assam and adjoining districts of Tripura using both ETKAC and ThDP measurements and to identify socioeconomic, environmental, and dietary factors associated with TDDs.

2 | Methodology

2.1 | Study Design and Setting

We conducted a community-based cross-sectional study between 2023 and 2024 in the North East states of India, the Barak Valley region of Assam state (Sribhumi [formerly Karimganj] and Hailakandi districts) and adjoining districts of Tripura state (North Tripura, Dhalai, and Unakoti). The study was designed to estimate the prevalence of thiamine deficiency among pregnant and lactating women and to identify associated socioeconomic, dietary, and environmental determinants.

2.2 | Study Population

The study population comprised pregnant and lactating women residing in selected households within the study districts. All pregnant women and lactating women (up to 24 months postpartum) who were usual residents of the selected villages and provided written informed consent were eligible for inclusion. Women who opted out of participation or blood sampling, were bedridden, or were consuming thiamine-containing supplements at the time of the survey were excluded.

2.3 | Sample Size and Sampling Procedure

The sample size was calculated assuming a thiamine deficiency prevalence of 20%, with an absolute precision of 4%, a design effect of 1.5 to account for cluster sampling, and a 10% allowance for nonresponse. This yielded a required sample size of 1320 participants (660 per state). A multistage cluster sampling design was employed. In each state, 60 villages (primary sampling units) were selected using probability proportional to size sampling. Within each selected village, Anganwadi Centre records maintained under the Integrated Child Development Services (ICDS) program were used as the sampling frame for identifying eligible pregnant and lactating women. From these lists, a minimum of 11 eligible women per cluster were selected using simple random sampling.

2.4 | Data Collection Procedures

Data were collected by trained field investigators using a standardized, pre-tested questionnaire administered through an electronic data capture platform (Open Data Kit) on tablet devices. The questionnaire captured information on sociodemographic characteristics, household environment, maternal and reproductive history, antenatal and delivery care, infant feeding practices, and participation in ICDS services.

Clinical assessment was performed to document signs and symptoms suggestive of thiamine deficiency. Information on recent

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morbidity among children under 2 years of age was also collected to contextualize maternal nutritional status.

Dietary practices relevant to thiamine intake and loss were assessed using a food frequency questionnaire covering the types of rice consumed, rice-processing and cooking practices, and whether fermented foods, betel nuts, or tea were consumed. A subsample of participants (one pregnant and one lactating from each village, accounting for approximately 15% of total participants) additionally underwent an interviewer-administered, multiple-pass 24-hour dietary recall, in which participants were asked to recall all foods and beverages consumed during the preceding 24 h, including their quantities. The multiple-pass method comprises a quick list of foods, a detailed description with portion-size estimation using standardized household measures, and a final review pass to capture commonly forgotten items.

2.5 | Blood Sample Collection and Handling

A total of 6.0 mL of venous blood was collected from the antecubital vein of each participant by trained phlebotomists into ethylenediaminetetraacetic acid (EDTA) vacutainers using standard aseptic procedures; plain (serum) tubes were not used, and the blood was not allowed to clot at any stage. The sample was divided into two 3.0 mL EDTA fractions: one fraction was retained as anticoagulated whole blood for hemogram estimation and for whole-blood ThDP measurement by HPLC, and the second fraction was processed for erythrocyte separation for the ETKAC assay. Immediately after collection, tubes were gently inverted several times to ensure adequate mixing with the anticoagulant and placed in insulated cold boxes maintained at 2°C–8°C. Samples were transported to the designated field processing laboratory within 4 h while maintaining the cold chain. The complete blood-processing workflow is shown in Figure S2.

2.5.1 | Sample Processing, Aliquoting, and Storage

At the field laboratory, hemoglobin estimation was performed on the whole-blood fraction using an automated hematology analyzer. The remaining anticoagulated whole blood from this fraction was aliquoted into two pre-labeled cryovials for ThDP estimation by HPLC. Because these aliquots were prepared from EDTA-anticoagulated whole blood that was never permitted to clot, the thiamine contained in erythrocytes and leukocytes was fully retained within the sample, preserving the integrity of the whole-blood ThDP measurement. Whole-blood aliquots designated for HPLC were stored at −20°C until shipment.

For ETKAC analysis, EDTA blood was centrifuged at 3000 rpm for 15 min at 4°C to separate plasma from erythrocytes, followed by a second centrifugation at 3000 rpm for 5 min to improve separation. The plasma and buffy coat were carefully removed, and the packed erythrocytes were washed three times with ice-cold isotonic saline (0.9% NaCl), with centrifugation at 1500 rpm for 15 min after each wash, to remove residual plasma and leukocytes. The washed erythrocytes were transferred into amber cryovials and stored at −20°C. Prior to ETKAC estimation, erythrocyte hemolysates were prepared from the washed erythrocytes according to the standard laboratory protocol.

All aliquots were transported under uninterrupted cold-chain conditions using dry ice (−80°C) to the Indian Council of Medical Research-National Institute of Nutrition (ICMR-NIN), Hyderabad. Upon receipt, samples were inspected for integrity, logged, and stored at −80°C until laboratory analysis. Temperature was monitored throughout storage and transportation to ensure sample integrity.

2.6 | Laboratory Assessment of Thiamine Status

Thiamine status was assessed using two complementary approaches: ETKAC as a functional biomarker of intracellular thiamine adequacy, and whole-blood ThDP concentration measured by HPLC as a biochemical indicator. ETKAC captures functional impairment of thiamine-dependent metabolism, while whole-blood ThDP provides a direct measure of the biologically active form of thiamine. The combined approach was used to improve classification of thiamine status and to address potential discordance between functional and biochemical indicators.

2.6.1 | Erythrocyte Transketolase Activation Coefficient

Functional thiamine status was assessed by measuring ETKAC in washed erythrocytes, following a standardized protocol based on published consensus recommendations [10]. Washed erythrocytes were thawed, mixed thoroughly, and lysed by adding two volumes of deionized water. Following centrifugation, the hemolysate supernatant was diluted with Tris buffer and used for determination of erythrocyte transketolase activity. Basal enzyme activity was measured spectrophotometrically by monitoring the rate of NADH oxidation at 340 nm. Parallel reactions containing exogenous ThDP were used to determine stimulated transketolase activity under identical assay conditions.

The ETKAC was calculated as the ratio of ThDP-stimulated to basal transketolase activity, with higher values indicating lower intracellular thiamine availability. ETKAC values were classified as normal (<1.15), marginal deficiency (1.15–1.25), and severe deficiency (>1.25), in accordance with internationally accepted thresholds.

Internal quality-control samples were included in each analytical batch. Samples with coefficients of variation exceeding predefined quality-control limits or demonstrating technical inconsistencies were reanalyzed, and measurements with implausible results were excluded from the final analysis.

2.6.2 | Thiamine Assessment by Using HPLC

Whole-blood ThDP concentration was measured using HPLC with fluorometric detection, using a validated commercial kit (ClinRep HPLC Complete Kit Vitamin B1 in Whole Blood, RECIPE Chemicals + Instruments GmbH, Munich, Germany); HPLC measurement of whole-blood ThDP has been described previously [11]. Whole-blood samples underwent protein precipitation and centrifugation. An aliquot of the supernatant was stabilized and subjected to pre-column oxidation under alkaline

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conditions, converting thiamine and its phosphate esters to highly fluorescent thiochrome derivatives.

Chromatographic separation was performed using a dedicated reverse-phase column under isocratic conditions, with post-column alkalinization to enhance fluorescence yield. Detection was carried out at an excitation wavelength of approximately 376 nm and an emission wavelength of approximately 435 nm. Quantification was based on the external standard method using a lyophilized whole-blood calibrator supplied with the kit. Analytical accuracy and precision were ensured through routine calibration and use of two levels of whole-blood quality-control material.

Whole-blood ThDP concentrations were quantified by HPLC. In accordance with the Institute of Medicine (IOM) guidance for the interpretation of thiamine status, whole-blood ThDP concentrations were classified as deficient (<70 nmol/L), marginal deficiency (70−90 nmol/L), and normal (≥90 nmol/L). Given the absence of universally accepted reference intervals for whole-blood ThDP and the variability in reported thresholds across analytical methods and study populations, these predefined cut-offs were adopted to ensure consistency in classification. We note that a higher whole-blood threshold of <95 nmol/L has also been proposed to indicate deficiency [12]; applying this more conservative cut-off would increase the estimated prevalence, and our use of the lower cut-off should, therefore, be regarded as a conservative estimate of thiamine deficiency in this population.

2.7 | Data Quality Assurance

Whole-blood ThDP concentrations were measured using a validated HPLC method with documented intra-assay and inter-assay coefficients of variation of 2.7% and 4.2%, respectively. ETKAC analysis was performed using standardized protocols with three internal quality control materials included in each analytical run, and assay performance was monitored to maintain between-batch coefficients of variation below the recommended 5% threshold. All laboratory results underwent independent verification before linkage with the field database. Samples yielding biologically implausible ETKAC values (<0.9 or >1.6), technical assay failure, damaged EDTA tubes, evidence of sample degradation, or analytical failure were excluded from analysis. No numerical cut-offs were applied to define implausible ThDP values; instead, exclusions were based solely on pre-analytical and analytical quality criteria.

2.8 | Statistical Analysis

Data collected in the field were transferred to a secure central server at the ICMR−National Institute of Nutrition (ICMR-NIN). The data were extracted from secure central servers and subjected to rigorous quality checks, including range, consistency, and logical validation. No imputation was performed for missing data. Descriptive statistics were used to summarize participant characteristics. Continuous variables were reported as means with standard deviation (SD) or medians with interquartile range (IQR), and categorical variables as frequencies and percentages.

Prevalence of thiamine deficiency was estimated with 95% confidence intervals calculated using the Wilson score method. Regression analyses were performed using standard logistic regression models. Given logistical constraints, cluster-robust variance estimation was not applied; this is addressed explicitly as a limitation. Univariable logistic regression was used to determine the associations between thiamine deficiency and potential explanatory variables. Variables with a p value <0.25 in the univariable analysis and those considered epidemiologically relevant were considered for inclusion in separate multivariable logistic regression models for ThDP-defined and ETKAC-defined suboptimal thiamine status. Candidate variables included state, place of residence, education, occupation, religion, caste/community, type of house, cooking fuel, source of drinking water, sanitary latrine use, pregnancy complications, antenatal care provider, place of delivery, monetary assistance received for delivery, initiation of breastfeeding (among lactating women only), consumption of salted tea, tea after meals, betel nut, cooked fermented fish/paste, white rice consumption, parboiled rice consumption, stored rice consumption, and frequency of rice washing. Variables exhibiting evidence of multicollinearity were not entered simultaneously into the same model. Adjusted odds ratios (aORs) with 95% confidence intervals (CIs) were reported. A two-sided p value <0.05 was considered statistically significant. All analyses were performed using R software (version 4.5.2).

2.9 | Ethical Considerations

The study protocol was approved by the Institutional Ethics Committee of the ICMR−National Institute of Nutrition, Hyderabad (IEC Number-NIN- CR/01/II/2022). Written informed consent was obtained from all participants aged 18 years or older. Permissions were obtained from the relevant state and district authorities in Assam and Tripura before initiation of field activities. Participant confidentiality was maintained throughout the study.

3 | Results

Pregnant and lactating women from the states of Assam and Tripura, India, were screened for eligibility and enrolled into the study between 2023 and 2024. A total of 1329 pregnant and lactating women were initially enrolled and interviewed in the community. All participants provided sociodemographic, maternal health, and dietary information. Of these, 1083 women had complete questionnaire data and valid biochemical measurements and were included in the final analytical sample. A total of 246 women were excluded from the final analysis due to implausible or technically invalid ETKAC values, invalid or unreliable ThDP measurements, or laboratory quality control failure (including hemolysis, inadequate sample volume, or cold-chain breach). Among the 1083 women included in the analysis, 599 were pregnant and 484 were lactating. A subsample of 175 women (approximately 15%) additionally underwent 24-hour dietary recall assessment for quantitative dietary intake analysis. All included participants contributed to the estimation of thiamine deficiency prevalence and associated determinants (Figure 1).

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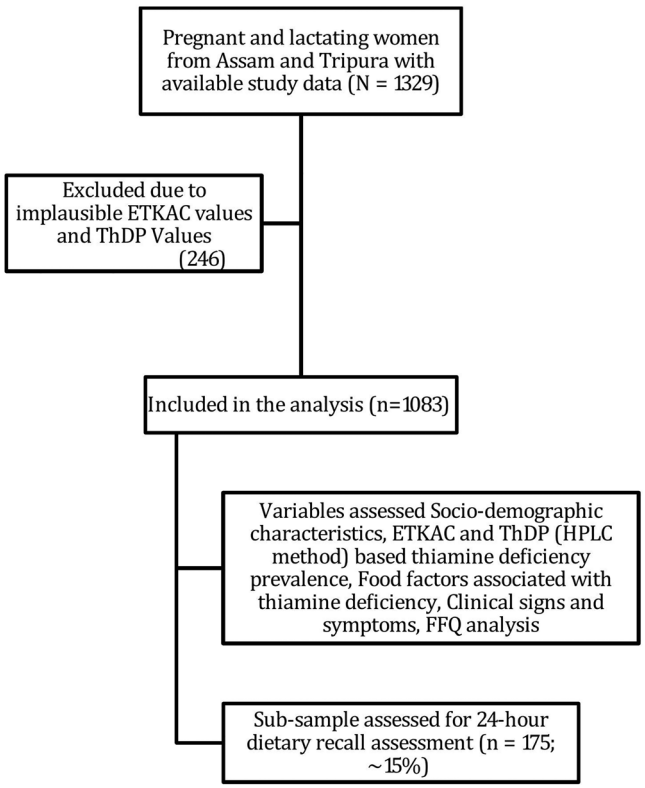


FIGURE 1 | Study flow diagram showing enrollment, exclusions, and final analytical sample of pregnant and lactating women in Barak Valley, Assam and Tripura during 2023–2024.

3.1 | Sociodemographic, Maternal Characteristics, and Dietary Practices

Table 1 describes the sociodemographic characteristics, household environment, maternal health indicators, and dietary practices of pregnant and lactating women included in the analysis ($n = 1083$), stratified by pregnancy and lactation status.

Over half of the participants were from Assam (54.5%), with the remainder from Tripura (45.5%). Most women lived in rural or tribal areas (73.6%), with slightly higher rural representation among pregnant women. The majority had secondary-level education, and nearly all were homemakers.

In terms of social characteristics, 62.1% of participants identified as Hindu, followed by Muslims (31.5%) and Christians or other religions (6.4%). Approximately one-third of women belonged to scheduled caste (SC) or scheduled tribe (ST) communities (31.6%), while 24.1% were from other backward castes. Nearly half of households relied on unclean cooking fuel (48.2%), and the vast majority used unprotected drinking-water sources (89.7%). Although most women reported using sanitary latrines (73.9%), a substantial minority (26.1%) did not. Housing conditions were mixed, with 29.1% living in kutcha houses and 22.8% living in semi-pucca houses.

Most women received antenatal care from nonphysician healthcare workers (70.4%), and a high proportion reported at least one pregnancy-related condition, predominantly anemia and minor self-reported morbidities (77.9%). Among lactating women, most delivered in health institutions (90.9%), though fewer than half received monetary assistance. The majority of mothers initiated breastfeeding within 1 h of birth (82.0%). Dietary practices like consumption of salted tea, betel nuts, and cooked fermented fish were more prevalent. Nearly all women consumed white rice as the staple food, with most washing rice two or more times before cooking.

3.2 | Prevalence of Thiamine Deficiency Based on Whole-Blood ThDP Concentration

Figure 2 shows that across reproductive groups and both states, a substantial proportion of women exhibited suboptimal biochemical thiamine status (deficient and marginal combined), indicating a considerable burden of inadequate thiamine status. In Assam, suboptimal status affected 24.7% of pregnant women, 16.0% of lactating women, and 20.9% overall (both groups combined), with the highest prevalence among pregnant women. In Tripura, although prevalence was lower, suboptimal status remained notable, affecting 22.8% of pregnant women, 14.9% of lactating women, and 19.3% overall (both groups combined). When pooled across states, suboptimal biochemical thiamine status affected approximately 20.1% of women (deficient 4.9%, marginal 15.2%). Mean whole-blood ThDP and ETKAC values, together with the distribution of deficient, marginal, and normal status by pregnancy/lactation status and state, are summarized in Table 2.

3.3 | Prevalence of Thiamine Deficiency Based on the ETKAC Method

Figure 3 shows that across all reproductive groups and both states, ETKAC-based assessment revealed a substantial burden of thiamine deficiency, indicating impaired functional thiamine status in a significant proportion of women. In Assam, suboptimal functional thiamine status (severe and marginal deficiency combined) affected 32.1% of pregnant women, 27.0% of lactating women, and 29.8% overall. The highest prevalence was observed among pregnant women, reflecting increased metabolic demand during gestation.

In Tripura, although overall deficiency prevalence was comparatively lower, thiamine deficiency remained prominent, particularly among pregnant women. Suboptimal status was identified in 10.6% of pregnant women, 8.1% of lactating women, and 9.5% overall, indicating that a meaningful proportion of women across all reproductive stages had suboptimal functional thiamine status.

When data from Assam and Tripura were pooled, thiamine deficiency based on ETKAC was 20.6% across groups, with the greatest burden consistently observed among pregnant women and those experiencing combined pregnancy and lactation. Even among lactating women, often considered nutritionally protected, 18.4% exhibited functional evidence of deficiency.

Overall, ETKAC findings indicate that functional thiamine deficiency is a significant public health concern in this population. Severe deficiency (ETKAC >1.25) was less frequent than marginal deficiency; considered separately, severe deficiency affected 8.5%

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TABLE 1 | Sociodemographic, maternal characteristics, and dietary practices among pregnant and lactating women in Barak Valley, Assam and Tripura during 2023–2024 ($n = 1083$).

Variable	Category	Pregnant *n* (%)	Lactating *n* (%)	Total *n* (%)
State	Assam	327 (54.6)	263 (54.3)	590 (54.5)
	Tripura	272 (45.4)	221 (45.7)	493 (45.5)
Residence	Rural/tribal	450 (75.1)	347 (71.7)	797 (73.6)
	Urban	149 (24.9)	137 (28.3)	286 (26.4)
Education status	Never went to school	21 (3.5)	34 (7.0)	55 (5.1)
	Primary	39 (6.5)	38 (7.9)	77 (7.1)
	Secondary	503 (84.0)	375 (77.5)	878 (81.1)
	Graduate and above	36 (6.0)	37 (7.6)	73 (6.7)
Occupation status	Home maker	587 (98.0)	469 (96.9)	1056 (97.5)
	Daily wage	4 (0.7)	4 (0.8)	8 (0.7)
	Employed	8 (1.3)	11 (2.3)	19 (1.8)
Religion	Hindu	347 (57.9)	326 (67.4)	673 (62.1)
	Muslim	210 (35.1)	131 (27.1)	341 (31.5)
	Christian and others	42 (7.0)	27 (5.6)	69 (6.4)
Caste/community	Scheduled caste and scheduled tribe	181 (30.2)	161 (33.3)	342 (31.6)
	Backward caste	131 (21.9)	130 (26.9)	261 (24.1)
	Others	287 (47.9)	193 (39.9)	480 (44.3)
Cooking fuel	Clean fuel	308 (51.4)	253 (52.3)	561 (51.8)
	Unclean fuel	291 (48.6)	231 (47.7)	522 (48.2)
Drinking water source	Protected water facility	64 (10.7)	47 (9.7)	111 (10.3)
	Unprotected water facility	535 (89.3)	437 (90.3)	972 (89.7)
Use of sanitary latrine	Using	459 (76.6)	341 (70.5)	800 (73.9)
	Not using	140 (23.4)	143 (29.5)	283 (26.1)
Type of house	Kutcha	161 (26.9)	154 (31.8)	315 (29.1)
	Pucca	298 (49.7)	223 (46.1)	521 (48.1)
	Semi-pucca	140 (23.4)	107 (22.1)	247 (22.8)
Antenatal care (ANC) conducted by[a]	Doctor	171 (30.0)	139 (29.1)	310 (29.6)
	Other healthcare worker	400 (70.0)	338 (70.9)	738 (70.4)
Pregnancy complication[b]	No	137 (22.9)	102 (21.1)	239 (22.1)
	Yes	462 (77.1)	382 (78.9)	844 (77.9)
Place of delivery[c]	Home	NA	44 (9.1)	44 (4.1)
	Institutional	NA	440 (90.9)	440 (40.6)
Money received for delivery[c]	Not received	NA	302 (62.4)	302 (27.9)
	< ₹10,000	NA	176 (36.4)	176 (16.3)
	≥ ₹10,000	NA	6 (1.2)	6 (0.6)
Initiation of breastfeeding[c]	First 1 h	NA	397 (82.0)	397 (36.7)
	1 h to 1 day	NA	73 (15.1)	73 (6.7)
	> 1 day	NA	14 (2.9)	14 (1.3)

(Continues)

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TABLE 1 | (Continued)

Variable	Category	Pregnant *n* (%)	Lactating *n* (%)	Total *n* (%)
Tea with salt	Yes	299 (49.9)	240 (49.6)	539 (49.8)
	No	300 (50.1)	244 (50.4)	544 (50.2)
Tea after meals	Yes	12 (2.0)	20 (4.1)	32 (3.0)
	No	587 (98.0)	464 (95.9)	1051 (97.0)
Betel nut consumption	Yes	347 (57.9)	283 (58.5)	630 (58.2)
	No	252 (42.1)	201 (41.5)	453 (41.8)
Cooked fermented fish or paste consumption	Yes	491 (82.0)	389 (80.4)	880 (81.3)
	No	108 (18.0)	95 (19.6)	203 (18.7)
White rice consumption	Yes	584 (97.5)	459 (94.8)	1043 (96.3)
	No	15 (2.5)	25 (5.2)	40 (3.7)
Parboiled rice consumption	Yes	5 (0.8)	6 (1.2)	11 (1.0)
	No	594 (99.2)	478 (98.8)	1072 (99.0)
Stored rice consumption	Yes	10 (1.7)	8 (1.7)	18 (1.7)
	No	589 (98.3)	476 (98.3)	1065 (98.3)
Rice washed ≥2 times	Yes	478 (79.8)	379 (78.3)	857 (79.1)
	No	121 (20.2)	105 (21.7)	226 (20.9)

Note: Values are *n* (%). Percentages for pregnant and lactating women are column percentages; total percentages are calculated using the overall sample.

[a]ANC data available for 1048 women.

[b]Included self-reported anemia, nausea/vomiting, weakness, dizziness, leg cramps, edema, and other minor ailments experienced during pregnancy.

[c]Variables applicable only to lactating women. NA-Not applicable, as they are pregnant women and the variables do not apply to them.

Kutcha: House constructed predominantly using temporary materials such as mud, bamboo, thatch, or unburnt bricks. Semi-pucca: House constructed using a combination of temporary and permanent materials. Pucca: House constructed entirely using durable materials such as burnt bricks, cement, and concrete. Clean fuel: LPG, electricity, or biogas. Unclean fuel: Firewood or kerosene. Tea with salt: Traditional salted tea prepared with tea leaves, salt, and water (sometimes with milk), commonly consumed in parts of Northeast India.

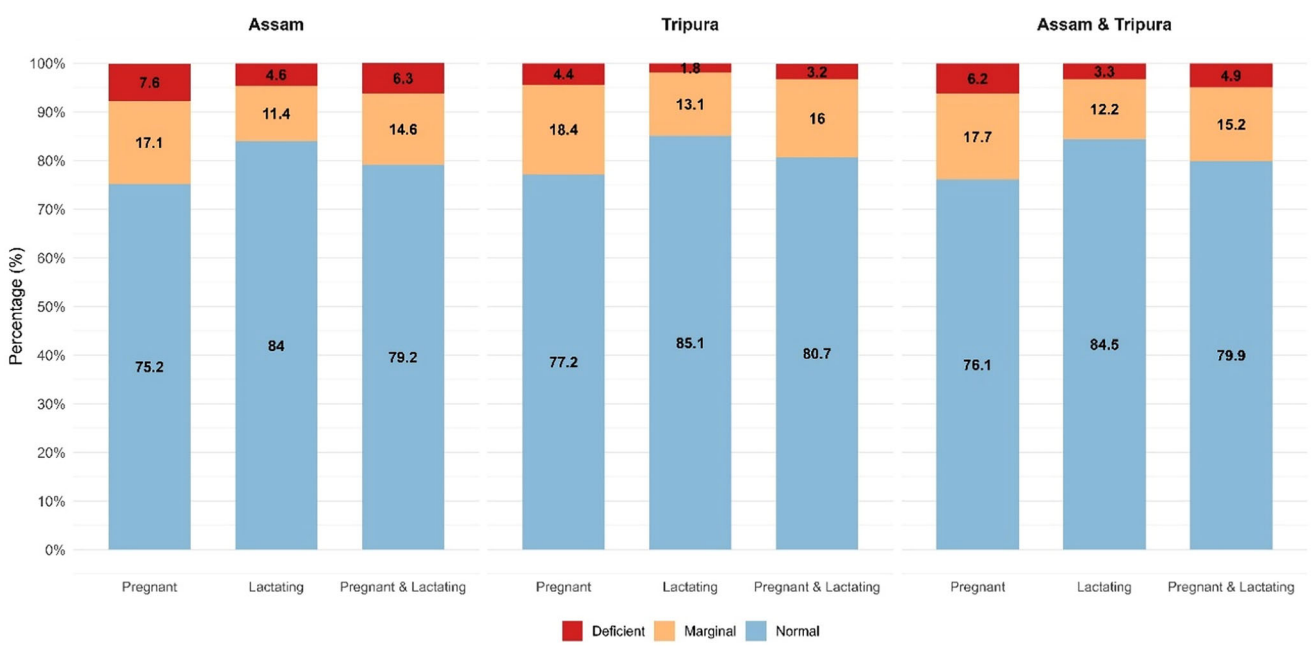


FIGURE 2 | Prevalence of thiamine deficiency among pregnant and lactating women in Barak Valley, Assam and Tripura during 2023–2024, based on whole-blood ThDP concentration assessed by using the HPLC method (n = 1083). Thiamine status categories: deficient <70 nmol/L, marginal 70–90 nmol/L, normal ≥90 nmol/L.

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TABLE 2 | Whole-blood thiamine diphosphate (ThDP) concentrations, erythrocyte transketolase activation coefficient (ETKAC) ratios, and the distribution of deficient, marginal, and normal thiamine status by pregnancy/lactation status and state among women in Barak Valley, Assam and Tripura, 2023–2024 ($n = 1083$).

Group	*n*	Whole-blood ThDP (nmol/L), mean ± SD	ETKAC ratio, mean ± SD	ThDP deficient (<70) %	ThDP marginal (70–90) %	ThDP normal (≥90) %	ETKAC deficient (>1.25) %	ETKAC Marginal (1.15–1.25) %	ETKAC Normal (<1.15) %
Overall	**1083**	**120.5 ± 36.1**	**1.07 ± 0.13**	**4.9**	**15.2**	**79.9**	**8.5**	**12.1**	**79.4**
Pregnant	599	117.1 ± 36.5	1.07 ± 0.13	6.2	17.7	76.1	8.7	13.7	77.6
Lactating	484	124.7 ± 35.1	1.08 ± 0.13	3.3	12.2	84.5	8.3	10.1	81.6
Assam (all)	590	122.8 ± 39.3	1.10 ± 0.15	6.3	14.6	79.2	13.7	16.1	70.2
Pregnant	327	119.3 ± 39.4	1.10 ± 0.16	7.6	17.1	75.2	14.4	17.7	67.9
Lactating	263	127.2 ± 38.8	1.10 ± 0.14	4.6	11.4	84.0	12.9	14.1	73.0
Tripura (all)	493	117.7 ± 31.5	1.05 ± 0.10	3.2	16.0	80.7	2.2	7.3	90.5
Pregnant	272	114.4 ± 32.4	1.04 ± 0.10	4.4	18.4	77.2	1.8	8.8	89.3
Lactating	221	121.8 ± 29.9	1.05 ± 0.10	1.8	13.1	85.1	2.7	5.4	91.9

Note: Values are mean ± SD for ThDP and ETKAC, and column percentages for status categories. ThDP status (whole blood): deficient <70 nmol/L, marginal 70–90 nmol/L, normal ≥90 nmol/L. ETKAC status: deficient >1.25, marginal 1.15–1.25, normal <1.15. Percentages within each biomarker sum to 100% (subject to rounding).

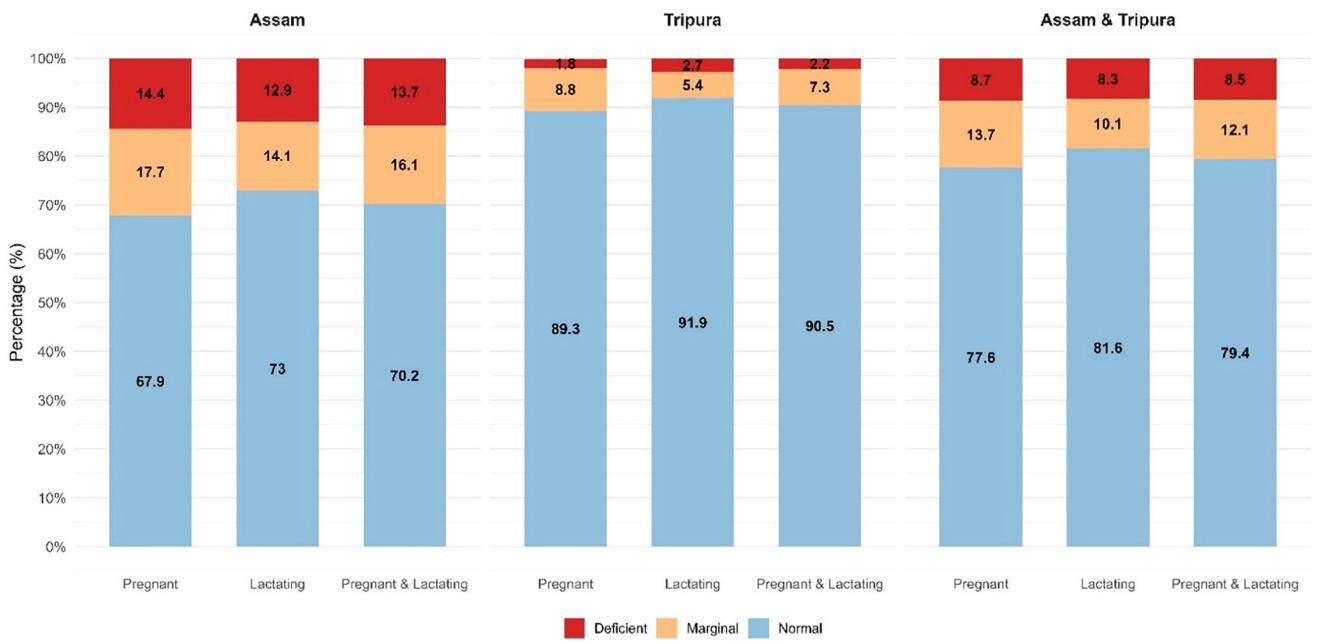


FIGURE 3 | Prevalence of thiamine deficiency among pregnant and lactating women in Barak Valley, Assam and Tripura during 2023–2024, assessed by using the ETKAC method ($n = 1083$). Thiamine status categories: deficient (severe) ETKAC >1.25, marginal (insufficient) 1.15–1.25, normal <1.15.

and marginal deficiency 12.1% of women. The combined prevalence (20.6%, as reported above) indicates that approximately one in five women had impaired functional thiamine status. Because marginal deficiency may precede overt clinical manifestations, these findings suggest that a substantial burden of thiamine insufficiency remains clinically unrecognized and warrants preventive population-level interventions.

3.4 | Concordance Between ThDP and ETKAC Classifications

For the concordance and determinant analyses, thiamine deficiency was defined as suboptimal status (deficient or marginal: whole-blood ThDP <90 nmol/L; ETKAC ≥1.15). The two assays showed almost the same deficiency prevalence: HPLC identified 218 out of 1083 participants (20.1%) as deficient, while ETKAC identified 223 (20.6%). However, the two markers largely did not flag the same women: of the 393 participants classified as suboptimal by at least one assay, only 48 (12%) were flagged by both, while 345 were suboptimal on one marker but normal on the other. Thus, the ≈20% identified by ThDP and the ≈20% identified by ETKAC were substantially nonoverlapping groups rather than the same individuals (Table S1 and Figure S3). A cross-tabulation of thiamine (Table S1) showed that the two markers agreed on 738 participants (68.1% raw agreement), with 690 classified as normal and 48 as deficient. They disagreed on 345 participants (31.9%). After adjusting for chance agreement, which was high because about 80% of participants were classified as normal by both methods, Cohen's κ was very low (0.02). Because

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κ is strongly influenced by prevalence when most participants fall in one category (the "kappa paradox"), we also computed the prevalence-adjusted bias-adjusted kappa (PABAK = 0.36), which indicates only fair chance-corrected agreement. Together, these indicate that the two assays showed no better than chance agreement in classifying individuals beyond the shared "normal" category. The disagreement was balanced: 175 participants were normal by HPLC but deficient by ETKAC, and 170 were the opposite. The McNemar test was not significant ($p = 0.79$), showing that neither method tended to overestimate deficiency. Agreement was, therefore, concentrated in the shared "normal" category rather than in the identification of affected individuals. Overall, these results suggest that HPLC and ETKAC provide similar estimates of deficiency prevalence at the population level but are not interchangeable for identifying individual thiamine deficiency. This discordance is consistent with the different biological aspects the two markers measure: the circulating thiamine pool (HPLC) versus functional enzyme adequacy (ETKAC).

3.5 | Associations Between Factors and Thiamine Status

Table 3 presents unadjusted and adjusted associations between sociodemographic characteristics, household environment, maternal health factors, dietary practices, and thiamine deficiency among pregnant and lactating women, as assessed using HPLC- and ETKAC-based methods.

In the unadjusted analyses, ThDP-defined suboptimal thiamine status demonstrated marked socioeconomic gradients. Lower educational attainment was consistently associated with higher odds of deficiency, with women who never attended school showing nearly five-fold higher odds compared with graduates (OR 4.98, 95% CI 1.91–12.96). Residence in pucca housing, use of sanitary latrines, and employment status were associated with significantly lower odds of deficiency. Use of unclean cooking fuel was associated with almost a two-fold increase in deficiency risk (OR 1.96, 95% CI 1.45–2.66). Women from SC or ST communities had higher odds of deficiency compared with general caste women.

Dietary practices showed several significant associations with ThDP-defined suboptimal status. Consumption of betel nut, tea after meals, and parboiled rice was associated with higher odds of deficiency, whereas consumption of cooked fermented fish or paste was associated with lower odds, suggesting a potentially protective role. White rice consumption showed no significant association.

For ETKAC-defined suboptimal status, a partially distinct pattern was observed. Residence in Tripura was associated with substantially lower odds of deficiency than residence in Assam (OR 0.25, 0.17–0.35). Muslim religion, backward caste status, receipt of antenatal care from nonphysician healthcare workers, and delayed initiation of breastfeeding were associated with higher odds of ETKAC-defined suboptimal status. Maternal health service indicators, including pregnancy complications, place of delivery, and receipt of delivery-related financial incentives, showed no significant associations with thiamine deficiency by either method. Among dietary factors, stored rice consumption, washing rice two or more times before cooking, and consumption of salted tea were associated with higher odds of ETKAC-defined suboptimal status, whereas fermented food practices showed no significant associations.

After adjustment for sociodemographic, household, maternal, and dietary variables, fewer factors remained independently associated with ThDP-defined suboptimal status. Women belonging to SC or ST communities had significantly higher odds of deficiency than women from other caste groups (aOR 1.76, 95% CI 1.10–2.80), and use of unclean cooking fuel was also independently associated with increased odds (aOR 1.47, 95% CI 1.01–2.12). Among dietary factors, betel nut consumption was associated with higher odds of deficiency, whereas consumption of cooked fermented fish or fish paste was associated with lower odds. For ETKAC-defined suboptimal status, residence in Tripura was independently associated with lower odds of deficiency than residence in Assam (aOR 0.36, 95% CI 0.23–0.57). Stored rice consumption remained positively associated with deficiency, while washing rice two or more times showed a borderline positive association. Educational attainment, housing characteristics, water source, sanitation, maternal health indicators, rice consumption, and rice preparation practices were no longer independently associated after adjustment.

Overall, the multivariable analysis indicates that structural socioeconomic factors and specific dietary practices like betel nut consumption were independently associated with biochemical (ThDP) thiamine deficiency, whereas functional deficiency assessed by ETKAC was predominantly influenced by geographic variation and rice storage and handling behaviors. The divergence between models underscores the importance of considering both biochemical and functional assessments when evaluating determinants of thiamine deficiency in population-based studies.

3.6 | Dietary Pattern Analysis

Figure S1 illustrates the habitual dietary pattern among pregnant and lactating women. Cereals and roots/tubers were consumed daily by most participants, with polished white rice constituting the predominant staple food. In contrast, thiamine-rich foods, including green leafy vegetables, legumes, nuts, and animal-source foods, were consumed infrequently, most often on a weekly or occasional basis. Fish was the most commonly consumed animal-source food, whereas eggs, poultry, meat, fruits, and dairy products were consumed irregularly. Overall, the dietary pattern was characterized by a monotonous, carbohydrate-dense diet with limited dietary diversity and low consumption of thiamine-rich foods.

Table S2 compares nutrient and food group intakes between women with low and normal thiamine status based on ETKAC, where the low thiamine group comprises women with marginal or severe deficiency (ETKAC ≥1.15). Total energy intake and overall food group consumption were broadly similar between the two groups. However, women with low thiamine status had significantly lower dietary thiamine intake (0.73 vs. 0.82 mg/day; $p = 0.049$), protein intake (70.8 vs. 77.9 g/day; $p = 0.046$), and iron intake (13.0 vs. 22.5 mg/day; $p = 0.016$) than women with

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TABLE 3 | Unadjusted and adjusted odds ratios for factors like sociodemographic, maternal characteristics, and dietary practices associated with ThDP-defined and ETKAC-defined suboptimal thiamine status among pregnant and lactating women in Barak Valley, Assam and Tripura, India, 2023–2024 ($n = 1083$).

Variable	Category	ThDP deficiency (<70 nmol/L) Unadjusted OR (95% CI)	*p* value	ThDP deficiency (<70 nmol/L) aOR (95% CI)	*p* value	ETKAC deficiency (>1.25) Unadjusted OR (95% CI)	*p* value	ETKAC deficiency (>1.25) aOR (95% CI)	*p* value
State	Assam	Reference	—	Reference	—	Reference	—	Reference	—
	Tripura	0.91 (0.67–1.22)	0.519	1.05 (0.68–1.62)	0.814	**0.25 (0.17–0.35)**	**<0.001**	**0.36 (0.23–0.57)**	**<0.001**
Residence	Rural	Reference	—	Reference	—	Reference	—	Reference	—
	Urban	0.74 (0.52–1.06)	0.101	1.13 (0.76–1.68)	0.555	1.06 (0.76–1.48)	0.720	1.09 (0.74–1.60)	0.677
Education	Graduate or above	Reference	—	Reference	—	Reference	—	Reference	—
	Secondary	**2.23 (1.01–4.95)**	**0.048**	1.59 (0.70–3.63)	0.273	1.13 (0.62–2.07)	0.686	0.89 (0.47–1.72)	0.735
	Primary	**4.27 (1.71–10.67)**	**0.002**	2.56 (0.98–6.71)	0.055	1.02 (0.45–2.29)	0.963	0.83 (0.34–2.01)	0.678
	Never attended school	**4.98 (1.91–12.96)**	**0.001**	2.58 (0.92–7.21)	0.071	0.72 (0.28–1.85)	0.493	0.53 (0.18–1.54)	0.246
Occupation	Unemployed	Reference	—			Reference	—		
	Employed	**0.03 (0.003–0.39)**	**0.007**			**0.12 (0.02–0.88)**	**0.038**		
	Homemaker	**0.15 (0.04–0.64)**	**0.010**			0.26 (0.06–1.04)	0.057		
Religion	Christian/other	Reference	—	Reference	—	Reference	—	Reference	—
	Muslim	0.79 (0.44–1.40)	0.418	1.32 (0.58–3.01)	0.511	**3.83 (1.70–8.66)**	**0.001**	0.97 (0.35–2.66)	0.955
	Hindu	**0.50 (0.29–0.88)**	**0.016**	0.74 (0.39–1.39)	0.346	1.79 (0.80–4.01)	0.159	0.82 (0.34–2.01)	0.666
	General	Reference	—	Reference	—	Reference	—	Reference	—
Caste/community									
	Scheduled caste/tribe	**1.82 (1.19–2.79)**	**0.006**	**1.76 (1.10–2.80)**	**0.019**	0.92 (0.59–1.44)	0.711	1.00 (0.61–1.63)	0.999
	Other backward caste	**1.52 (1.01–2.30)**	**0.043**			**2.04 (1.38–3.00)**	**<0.001**		
Type of house	Kutcha	Reference	—	Reference	—	Reference	—	Reference	—
	Semi-pucca	0.69 (0.47–1.03)	0.069	0.69 (0.45–1.06)	0.087	1.39 (0.92–2.09)	0.113	1.33 (0.84–2.10)	0.222
	Pucca	**0.49 (0.35–0.69)**	**<0.001**	0.77 (0.49–1.21)	0.252	1.13 (0.79–1.62)	0.495	1.10 (0.69–1.77)	0.687
Cooking fuel	Clean fuel	Reference	—	Reference	—	Reference	—	Reference	—
	Unclean fuel	**1.96 (1.45–2.66)**	**<0.001**	**1.47 (1.01–2.12)**	**0.043**	1.24 (0.92–1.67)	0.153	1.29 (0.88–1.88)	0.186
Drinking water source	Protected	Reference	—	Reference	—	Reference	—	Reference	—
	Unprotected	0.72 (0.46–1.14)	0.159	0.80 (0.50–1.30)	0.370	0.71 (0.45–1.11)	0.129	0.66 (0.40–1.07)	0.089
Sanitary latrine use	Not using	Reference	—	Reference	—	Reference	—	Reference	—
	Using	**0.56 (0.41–0.77)**	**<0.001**	0.97 (0.65–1.46)	0.901	0.90 (0.65–1.25)	0.524	0.88 (0.57–1.34)	0.542
Pregnancy complications	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	1.04 (0.72–1.49)	0.839	0.93 (0.63–1.38)	0.721	1.15 (0.80–1.66)	0.446	1.16 (0.79–1.72)	0.451
ANC provider	Doctor	Reference	—			Reference	—		
	Other healthcare worker	1.20 (0.85–1.69)	0.286			**1.81 (1.26–2.60)**	**0.001**		
Place of delivery[a]	Home	Reference	—			Reference	—		
	Institutional	1.18 (0.48–2.89)	0.722			1.02 (0.45–2.27)	0.970		
Money received for delivery[a]	< ₹10,000	Reference	—			Reference	—		
	≥ ₹10,000	1.10 (0.12–9.82)	0.929			0.84 (0.09–7.38)	0.871		
	Not received	1.02 (0.61–1.70)	0.948			0.91 (0.56–1.46)	0.696		
Initiation of breastfeeding[a]	Within 1 h	Reference				Reference			
	1–24 h	1.89 (1.02–3.48)	0.042			0.43 (0.19-0.98)	0.045		
	>24 h	1.70 (0.46–6.27)	0.429			1.64 (0.50-5.35)	0.416		
Tea with salt	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	1.16 (0.86–1.56)	0.325	1.09 (0.77–1.54)	0.621	**1.89 (1.41–2.56)**	**<0.001**	1.15 (0.81–1.61)	0.443
Tea after meals	No	Reference	—			Reference	—		
	Yes	**3.23 (1.59–6.67)**	**0.001**			1.54 (0.70–3.33)	0.288		

(Continues)

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TABLE 3 | (Continued)

Variable	Category	ThDP deficiency (<70 nmol/L) Unadjusted OR (95% CI)	*p* value	ThDP deficiency (<70 nmol/L) aOR (95% CI)	*p* value	ETKAC deficiency (>1.25) Unadjusted OR (95% CI)	*p* value	ETKAC deficiency (>1.25) aOR (95% CI)	*p* value
Betel nut consumption	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	**1.56 (1.14–2.13)**	**0.005**	**1.52 (1.08–2.13)**	**0.016**	**1.59 (1.16–2.17)**	**0.003**	1.10 (0.78–1.54)	0.605
Cooked fermented fish or paste	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	**0.65 (0.46–0.93)**	**0.019**	**0.56 (0.38–0.82)**	**0.003**	0.95 (0.66–1.39)	0.818	1.11 (0.74–1.67)	0.622
White rice consumption	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	0.57 (0.29–1.15)	0.117	0.50 (0.23–1.06)	0.074	0.89 (0.42–1.89)	0.761	1.27 (0.51–3.10)	0.611
Parboiled rice consumption	No	Reference	—			Reference	—		
	Yes	**3.33 (1.02–11.11)**	**0.047**			0.38 (0.05–3.03)	0.361		
Stored rice consumption	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	1.14 (0.37–3.45)	0.823	0.53 (0.16–1.82)	0.311	**4.00 (1.56–10.00)**	**0.004**	**3.33 (1.15–10.00)**	**0.026**
Rice washed ≥2 times	No	Reference	—	Reference	—	Reference	—	Reference	—
	Yes	0.85 (0.60–1.22)	0.401	0.83 (0.52–1.33)	0.440	**3.23 (1.96–5.26)**	**<0.001**	1.72 (0.97–3.03)	0.061

Note: Odds ratios obtained from logistic regression analyses.
[a]Analyses restricted to lactating women only ($n = 484$).

normal thiamine status. No significant differences were observed for other nutrients or food groups.

Table S3 presents the mean percentage deficit in nutrient intake relative to the estimated average requirement (EAR) among pregnant and lactating women according to ETKAC-defined thiamine status (low = marginal or severe deficiency, ETKAC ≥1.15). Across both physiological groups, thiamine intake showed a very severe deficit (>50% of the EAR; pregnant: 53.8%, lactating: 52.3%), together with marked deficits in riboflavin (75.1% and 75.2%), folate (60.8% and 33.3%), calcium (45.3% and 51.2%), and vitamin A (42.5% and 60.0%). In contrast, deficits in energy (9.0% and 10.2%) and carbohydrate intake (3.6% and 3.0%) were relatively small, indicating that although energy requirements were largely met, diets were consistently poor in several essential micronutrients.

4 | Discussion

In this large community-based study from Northeast India, we show that thiamine deficiency remains common, largely silent, and preventable among pregnant and lactating women, with approximately one in five women exhibiting biochemical or functional deficiency and nearly one in 10 showing severe functional impairment. To our knowledge, this is among the largest community-based studies to simultaneously assess biochemical and functional thiamine status among pregnant and lactating women in India. These findings provide some of the strongest population-level evidence currently available that thiamine deficiency remains an important maternal nutrition problem in the country, extending beyond sporadic clinical outbreaks and hospital-based reports. The predominance of subclinical deficiency observed in this study further highlights that the public health burden is likely considerably greater than that reflected by clinically recognized beriberi alone, reinforcing the need for improved surveillance and early identification of at-risk population [1, 2].

The prevalence observed in the present study closely mirrors that reported among women of reproductive age in South and Southeast Asia, where community-based studies from Cambodia, Laos, Myanmar, Bangladesh, and other thiamine deficiency–endemic settings have documented biochemical or functional deficiency prevalences ranging from approximately 20% to 35% [1]. These populations share several characteristics with Northeast India, including heavy reliance on polished rice as the dietary staple, limited dietary diversity, and persistent socioeconomic disadvantage. Nationally representative data from Cambodia similarly demonstrated a high prevalence of biochemical thiamine deficiency among women of reproductive age, emphasizing that maternal thiamine deficiency remains an important but underrecognized public health concern in rice-dependent populations [1]. Collectively, these findings position Northeast India within a broader Asian belt where thiamine deficiency continues to persist despite improvements in maternal and child health services and challenge the perception that thiamine deficiency is no longer a significant nutritional problem in India [1, 2].

Within India, evidence on thiamine deficiency has largely been restricted to outbreak investigations and hospital-based case series describing infantile beriberi, postpartum neuropathy, and cardiac manifestations, particularly from Assam and neighboring northeastern states [7, 8]. More recently, a 2021 study [7] highlighted the "rediscovery" of TDDs in Northeast India, demonstrating that maternal deficiency remains substantially

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under-recognized in routine clinical practice despite continued occurrence of severe disease. Likewise, a 2020 study [13] reported clusters of infantile beriberi in rural Assam in which affected infants exhibited rapid clinical improvement following thiamine administration, strongly implicating maternal thiamine deficiency as the underlying cause. While these studies underscored the clinical severity of TDDs, they were unable to quantify the magnitude of deficiency at the population level. The present study addresses this important evidence gap by demonstrating that thiamine deficiency is widespread within the community and predominantly subclinical, suggesting that clinically overt beriberi likely represents only the visible manifestation of a much larger underlying burden. Similar observations have been reported from Laos and Cambodia, where community-based assessments identified substantial biochemical deficiency despite relatively few clinically recognized cases, underscoring the importance of detecting deficiency before irreversible neurological or cardiovascular complications develop [1, 3, 4].

Pregnant women consistently demonstrated a higher prevalence of thiamine deficiency than lactating women, a finding that is biologically plausible and consistent with current understanding of maternal thiamine physiology. Pregnancy is characterized by increased metabolic demand, accelerated carbohydrate metabolism, expansion of maternal blood volume, and active placental transport of thiamine to support fetal growth and development, resulting in substantially higher physiological requirements despite limited body stores [2, 14]. Because thiamine reserves are small and rapidly depleted when dietary intake is inadequate, pregnant women are particularly vulnerable to deficiency in populations consuming predominantly polished rice-based diets. Similar findings have recently been reported by a 2023 study [6], which observed a high prevalence of maternal thiamine deficiency during pregnancy in an endemic region and demonstrated associations with adverse fetal outcomes. Although lactation also increases maternal thiamine requirements because breast milk serves as the infant's primary source of thiamine, physiological adaptations following delivery together with differences in dietary intake, supplementation practices, and timing of assessment may partly explain the comparatively lower prevalence observed among lactating women in our study. Nevertheless, the persistence of deficiency across both physiological groups despite high antenatal care coverage suggests that existing maternal nutrition programs, which predominantly emphasize iron-folic acid and calcium supplementation, may inadequately address thiamine requirements during pregnancy and lactation. The higher ETKAC-defined suboptimal status observed among women receiving antenatal care from nonphysician providers and those with delayed breastfeeding initiation is most plausibly a marker of remoteness and social disadvantage rather than a causal effect of these services, paralleling the associations seen for SC/ST status and unclean cooking fuel.

Social disadvantage emerged as a central determinant of suboptimal biochemical thiamine status. Women belonging to SC or ST communities had significantly higher odds of ThDP-defined suboptimal status even after adjustment for other sociodemographic factors. Although caste itself is unlikely to be causally related to thiamine status, these findings probably reflect persistent structural inequities in access to nutritionally adequate diets, healthcare, and socioeconomic resources. Similar associations between social vulnerability, food insecurity, and thiamine deficiency have been reported across South and Southeast Asia, where marginalized populations dependent on subsistence agriculture and monotonous cereal-based diets experience disproportionately higher rates of deficiency [1, 2]. Likewise, the independent association between unclean cooking fuel and biochemical deficiency likely represents a proxy for long-term household deprivation rather than a direct biological determinant, highlighting the broader influence of social determinants on maternal nutritional status.

Dietary practices characteristic of the study population further support these observations. The near-universal reliance on polished white rice, frequent washing of rice before cooking, and low consumption of legumes, nuts, dairy products, and animal-source foods create a dietary pattern inherently vulnerable to thiamine deficiency. Milling removes much of the thiamine-rich bran and germ, while repeated washing and prolonged cooking further reduce the remaining thiamine content of rice before consumption [1]. Similar dietary practices have been described in Cambodia, Laos, and other thiamine-endemic regions, where polished rice remains the predominant staple and contributes substantially to inadequate thiamine intake [1, 3]. These findings suggest that thiamine deficiency in Northeast India is driven not by a single dietary exposure but by the cumulative effect of long-term dependence on nutritionally poor staple foods combined with limited dietary diversity.

Our multivariable analyses also identified associations with culturally embedded dietary practices. Women who did not consume cooked fermented fish or fish paste had significantly higher odds of suboptimal biochemical thiamine status, whereas betel nut consumption was associated with increased odds of deficiency. Similar observations were reported by a 1975 study [14] among rural populations in northeastern Thailand, where habitual betel nut chewing was associated with poorer thiamine status, while fermented fish consumption was associated with improved thiamine status. Although the underlying mechanisms remain incompletely understood, fermented fish may represent both a modest dietary source of thiamine and a marker of greater dietary diversity, whereas betel nut consumption may contribute to poorer thiamine status through dietary displacement or other metabolic mechanisms that require further investigation. Given the close cultural and dietary similarities between Northeast India and neighboring Southeast Asian populations, our findings provide contemporary support for these earlier observations while emphasizing the need for longitudinal studies to better understand these relationships.

Quantitative dietary assessment demonstrated that thiamine deficiency occurred within a broader pattern of multiple micronutrient inadequacies rather than as an isolated nutritional problem. More than half of pregnant and lactating women had inadequate thiamine intake, while substantial inadequacies were also observed for riboflavin, folate, calcium, vitamin A, and dietary fat. In contrast, deficits in energy intake were comparatively modest, suggesting that caloric sufficiency did not necessarily translate into adequate micronutrient intake. Furthermore, women with ETKAC-defined suboptimal status consumed significantly lower amounts of thiamine, protein, and iron than women with normal status. While the elevated ETKAC is attributable specif-

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ically to inadequate thiamine intake, the accompanying lower protein and iron intakes indicate that this thiamine shortfall occurred within a broader pattern of poor overall diet quality rather than in isolation. This pattern is consistent with the concept of "hidden hunger," in which diets provide adequate calories but insufficient quantities of essential vitamins and minerals necessary for optimal health and metabolic function [15, 16]. Consequently, interventions addressing only individual micronutrients may have limited effectiveness in populations experiencing widespread dietary inadequacy.

4.1 | Strengths and Limitations

A major strength of this study is the simultaneous use of whole-blood thiamine (ThDP) and ETKAC, which provided complementary insights into thiamine status. Although prevalence estimates were similar, determinants differed meaningfully. ThDP-defined suboptimal status was associated with markers of structural disadvantage, whereas ETKAC-defined suboptimal status was more sensitive to geographic context and food practices. These findings reinforce emerging consensus that reliance on a single biomarker may underestimate the true burden of thiamine deficiency, and that biochemical and functional measures capture distinct but overlapping dimensions of risk.

Notably, maternal health-service indicators including antenatal care provider, institutional delivery, and receipt of delivery-related cash benefits were not independently associated with thiamine status. This finding suggests that existing maternal health platforms in India may not adequately address thiamine or broader dietary quality, leaving a critical blind spot in current maternal nutrition programming.

Certain limitations should be acknowledged. The analysis did not explicitly account for clustering at the village level despite the multistage sampling design, so standard errors are likely underestimated, and the confidence intervals for borderline associations (e.g., unclean cooking fuel and SC/ST status) should be interpreted with caution; cluster-robust or survey-weighted variance estimation would be preferable and is planned for subsequent analyses. Given the consistency, direction, and magnitude of observed associations across both biochemical and functional biomarkers, however, the overall interpretation and public health implications are unlikely to be materially altered. In addition, several exposures were reported by only a small number of women (e.g., stored rice and parboiled rice consumption), so the corresponding odds ratios have wide confidence intervals and should be regarded as hypothesis-generating. In addition, the cross-sectional design limits causal inference regarding identified determinants. Although a range of socioeconomic, dietary, and maternal factors were assessed, parity was not included in the analytical models. Repeated pregnancies and prolonged lactation may contribute to maternal nutrient depletion, including thiamine depletion, and residual confounding by parity cannot be excluded. Finally, excluded participants did not differ systematically in field-level eligibility criteria, as exclusions were driven by laboratory quality-control thresholds.

Together, these findings indicate that thiamine deficiency among pregnant and lactating women in Northeast India is driven more by social disadvantage and erosion of protective dietary practices than by access to maternal health services and warrants renewed attention within maternal nutrition programs to prevent avoidable maternal and infant morbidity and mortality.

5 | Conclusions

Thiamine deficiency remains common, largely silent, and preventable among pregnant and lactating women in Northeast India. Approximately one in five women had suboptimal thiamine status (deficient or marginal) using either biomarker. The burden is shaped primarily by social disadvantage, monotonous rice-based diets, and culturally embedded food practices, rather than by gaps in maternal health-service utilization.

These findings have clear policy implications. Thiamine deficiency should be explicitly recognized within maternal nutrition strategies in India, particularly in high-risk regions such as Northeast India. Targeted thiamine supplementation or use of prenatal multiple micronutrient supplements containing thiamine, dietary diversification strategies, and consideration of population-level fortification should be prioritized in high-risk regions to prevent avoidable maternal and infant morbidity.

Author Contributions

M.K.M. and R.K.: Conceptualization, data curation, formal analysis, investigation, methodology, writing – original draft, writing – review and editing; E.T.R., S.R.N., and R.P.: Conceptualization, data curation, investigation, writing – review and editing; S.P., V.R.R., H.P., K.R., S.M., and K.G,: Data curation, data analysis, writing – review and editing; S.S., S.V.M., C.N., and O.M.: Data curation, writing – review and editing; S.F.R., S.R.M.G., R.R.K., J.J.B.G., F.G., and M.B.: Conceptualization, writing – review and editing.

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Peer Review

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