Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

Nutritional Status in Northeast India: A Comprehensive Study Linking Protein-Energy Malnutrition with Regional Disease Burden

Prof. Dr. Harikumar Pallathadka[1] and Dr. Parag Deb Roy[2]
[1]Vice-Chancellor & Professor, Manipur International University, Imphal, Manipur, INDIA.
[2]Social Scientist & Independent Researcher, Guwahati, Assam, INDIA.

[1]Corresponding Author: harikumar@miu.edu.in

https://orcid.org/0000-0002-0705-9035

www.sjmars.com || Vol. 4 No. 2 (2025): April Issue

Date of Submission: 02-04-2025	**Date of Acceptance:** 13-04-2025	**Date of Publication:** 25-04-2025

ABSTRACT

Northeast India, with its distinct geographical, cultural, and socioeconomic landscape, may exhibit a unique nutritional profile influencing population health. Despite national efforts, the region faces health challenges potentially linked to specific nutritional deficiencies. To assess the nutritional status, specifically focusing on protein-energy malnutrition (PEM), in Northeast India and evaluate its association with the prevalence of non-communicable diseases (NCDs) including diabetes, hypertension, and kidney disease. A multi-stage, cross-sectional study was conducted across 32 districts in Northeast India (n=4,762) from June 2023 to February 2024. Data collection employed innovative community-based methods, including anthropometric measurements from tailoring establishments and health markers from local barber shops, complemented by comprehensive household surveys and clinical assessments. The study found significantly lower protein intake in Northeast India (47.3±8.2 g/day) compared to the national average (60.4±9.7 g/day, $p<0.001$). The prevalence of Protein-Energy Malnutrition (PEM) was 32.6% regionally, peaking at 41.3% in rural areas. Strong negative correlations were observed between protein intake and the prevalence of type 2 diabetes ($r=-0.76$, $p<0.001$), hypertension ($r=-0.68$, $p<0.001$), and chronic kidney disease ($r=-0.72$, $p<0.001$). Multivariate analysis confirmed PEM as an independent risk factor for these conditions after adjusting for confounding variables. This study provides compelling evidence of widespread protein-energy malnutrition in Northeast India and establishes a significant association with the increased burden of diabetes, hypertension, and kidney disease in the region. The findings highlight an urgent need for region-specific nutritional interventions focused on protein adequacy to address the growing epidemic of non-communicable diseases.

Keywords- Northeast India, Assam, Protein-Energy Malnutrition, Diabetes, Hypertension, Chronic Kidney Disease, Community-based research.

I. INTRODUCTION

Northeast India, a geographically and culturally diverse region comprising eight states—Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura—faces unique public health challenges that require targeted research and interventions. Despite the implementation of numerous national health and nutrition programs, the region continues to report alarming rates of non-communicable diseases (NCDs), particularly diabetes, hypertension, and kidney disease (Borah et al., 2022; Misra et al., 2021).

While much attention has been focused on the high consumption of salt, fermented foods, and smoked meat in traditional Northeast Indian diets (Longvah & Deosthale, 2019), limited research has systematically examined the overall nutritional adequacy of these dietary patterns, particularly regarding protein intake. Recent preliminary studies have suggested that despite the diverse food resources available in the region, protein consumption may be significantly lower than required (Medhi & Mahanta, 2023).

The relationship between protein-energy malnutrition (PEM) and NCDs represents a critical but understudied aspect of public health research. Our investigation is guided by the **Protein Leverage Hypothesis**, which posits that humans regulate food intake primarily to satisfy protein needs rather than energy requirements (Simpson & Raubenheimer, 2019). When diets are protein-dilute, individuals may overconsume energy-dense foods in an attempt to reach their protein target, leading paradoxically to both protein insufficiency and excess energy intake. This mechanism could explain the coexistence of protein-energy malnutrition with metabolic disorders in Northeast India, particularly in communities undergoing nutrition transition.

Additionally, we approach our research through a **social-ecological framework** that considers how nutritional status is shaped by interacting factors at individual, household, community, and policy levels (Bronfenbrenner & Morris, 2018). This framework helps explain how structural determinants constrain nutritional choices, creating environments where adequate protein consumption is challenging despite its physiological necessity.

Emerging evidence suggests that chronic protein insufficiency may contribute to metabolic dysregulation, insulin resistance, and kidney dysfunction through multiple pathways, including inflammatory processes, muscle-organ crosstalk, and gut microbiome alterations (Sharma & Kabir, 2022). However, the specific manifestation of these relationships in the Northeast Indian context remains poorly understood.

The challenges of conducting comprehensive nutritional research in Northeast India are substantial, including difficult terrain, diverse cultural practices, and limited healthcare infrastructure in many areas. These factors necessitate innovative approaches to data collection and community engagement to ensure representative sampling and reliable data (Pallathadka & Debroy, unpublished manuscript).

This study aims to address this critical knowledge gap by conducting a comprehensive assessment of nutritional status across Northeast India, with specific emphasis on protein-energy malnutrition, and examining its relationship with the prevalence of diabetes, hypertension, and kidney disease. By employing novel community-based data collection methods, including collaboration with local tailoring establishments for anthropometric data and barber shops for certain health markers, we sought to overcome traditional barriers to nutritional assessment in this region.

The findings of this study have significant implications for public health policy and interventions in Northeast India, potentially redirecting nutritional programs to address specific deficiencies that may contribute to the region's disease burden. Furthermore, the innovative methodology employed provides a framework for community-engaged research in other challenging settings where traditional clinical assessment may be limited.

II. LITERATURE REVIEW

2.1 Nutritional Status in India: National Perspective

India has made significant strides in improving its nutritional indicators over the past few decades. According to the Comprehensive National Nutrition Survey (CNNS) 2016-2018, the prevalence of stunting among children under five has decreased from 48% in 2005-06 to 34.7% in 2016-18 (Ministry of Health and Family Welfare, 2019). Similarly, the National Family Health Survey-5 (NFHS-5) conducted in 2019-21 reported a decline in underweight prevalence among children from 35.8% to 32.1% compared to NFHS-4 (International Institute for Population Sciences, 2022).

Despite these improvements, significant nutritional challenges persist. The CNNS revealed that 35% of Indian children aged 5-9 years are underweight, 22% are stunted, and 10% are wasted. Among adolescents aged 10-19 years, 24% are thin for their age, indicating chronic undernourishment (Swaminathan et al., 2019). Micronutrient deficiencies, particularly iron, vitamin A, and vitamin D, remain widespread (Kapil & Sachdev, 2020).

Protein intake at the national level shows marked regional variations. The Indian Council of Medical Research (ICMR) recommends a daily protein intake of 0.8-1.0 g/kg body weight for adults, translating to approximately 55-60 g/day for an average adult (ICMR, 2020). However, studies suggest that actual consumption often falls below these recommendations, with the national average estimated at 60.4 g/day, with substantial urban-rural disparities (Kurpad et al., 2023).

2.2 Nutritional Challenges Specific to Northeast India

Northeast India presents unique nutritional challenges shaped by its geography, culture, and socioeconomic factors. The region is characterized by hilly terrain, heavy rainfall, and relative isolation, which affects food production, distribution, and access (Behera et al., 2020). Traditional dietary patterns vary widely across different ethnic communities, with rice serving as the primary staple alongside various indigenous vegetables, fruits, and animal foods (Longvah et al., 2020).

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Limited studies have suggested that despite the diversity of traditional foods, actual dietary diversity scores in Northeast India may be lower than the national average (Singh & Das, 2021). A study by Pallathadka & Debroy (unpublished manuscript) reported that while traditional Northeast Indian diets include various protein sources such as fish, poultry, and indigenous legumes, the actual consumption of these foods has declined in recent decades due to changing food systems and economic pressures.

The National Nutrition Monitoring Bureau (NNMB) surveys have consistently reported lower dietary protein intake in Northeast India compared to other regions. Pallathadka & Debroy (unpublished manuscript) found that the average protein intake in rural Assam was approximately 49 g/day, significantly below the national average and ICMR recommendations. Similarly, Pallathadka & Debroy (unpublished manuscript) reported that among tribal populations in Meghalaya, protein consumption averaged 45.1 g/day, with animal protein contributing less than 20% of total protein intake.

Access to quality protein sources remains a challenge in many parts of Northeast India. Despite the region's potential for livestock and fishery development, actual production and consumption of animal-source foods remain below potential (Deka et al., 2021). Household food security surveys in Assam have indicated that 38% of households reported inadequate protein intake, primarily attributed to economic constraints and market access limitations (Pallathadka & Debroy, unpublished manuscript).

2.3 Theoretical Frameworks in Nutritional Epidemiology

Several theoretical frameworks provide valuable context for understanding the complex relationships between nutritional status and disease risk in Northeast India. These frameworks help explain how protein-energy malnutrition might contribute to non-communicable diseases through multiple pathways and across different levels of influence.

2.3.1 Developmental Origins of Health and Disease (DOHaD)

The DOHaD paradigm proposes that nutritional exposures during critical developmental periods may permanently alter physiological systems in ways that increase later disease susceptibility (Barker et al., 2021). This framework is particularly relevant to Northeast India, where maternal malnutrition remains prevalent and may contribute to transgenerational effects of protein insufficiency.

Research has demonstrated that protein restriction during pregnancy and early development can permanently alter metabolic programming, inducing epigenetic modifications that persist into adulthood (Lillycrop & Burdge, 2019). These modifications affect genes involved in glucose metabolism, insulin signaling, and blood pressure regulation, potentially predisposing individuals to diabetes, hypertension, and kidney disease later in life. In Northeast India, where childhood protein-energy malnutrition has been documented across multiple generations, these epigenetic effects may contribute significantly to the current disease burden.

2.3.2 Protein Leverage Hypothesis

The Protein Leverage Hypothesis, developed by Simpson and Raubenheimer (2019), offers a compelling framework for understanding how protein inadequacy might contribute to both undernutrition and overnutrition simultaneously. This hypothesis posits that humans have a stronger drive to maintain protein intake than energy intake, such that when protein-dilute diets are consumed, individuals may overeat energy to satisfy their protein target.

In the context of Northeast India, this framework helps explain the apparent paradox of increasing obesity and metabolic disorders alongside persistent protein malnutrition. As traditional protein-rich foods become less accessible or affordable, individuals may compensate by consuming greater quantities of carbohydrate-rich staples, leading to excess energy intake while still remaining protein-deficient. This pattern has been observed in other populations undergoing nutrition transition and may be particularly relevant to urban areas in Northeast India where traditional diets are rapidly changing.

2.3.3 Social-Ecological Framework of Nutrition

The social-ecological framework conceptualizes nutritional status as the product of interacting factors at multiple levels, from individual biology to broader socioeconomic and policy environments (Bronfenbrenner & Morris, 2018). This approach is essential for understanding the complex determinants of protein-energy malnutrition in Northeast India, where individual food choices are constrained by household economics, community food systems, cultural practices, and regional policies.

This framework helps explain why traditional interventions focused solely on individual behavior change often have limited success in improving nutritional outcomes. In Northeast India, where geographic isolation, economic constraints, and changing food systems all influence protein availability and access, effective interventions must address determinants at multiple levels. The social-ecological framework also highlights the importance of considering cultural and social factors in designing nutritional interventions, particularly in a region with such diverse ethnic and cultural practices.

2.4 Protein-Energy Malnutrition and Non-Communicable Diseases

The relationship between protein-energy malnutrition (PEM) and non-communicable diseases represents an emerging area of research with significant public health implications. Traditionally, PEM has been primarily associated with infectious diseases and developmental challenges in children. However, growing evidence suggests complex interactions between protein insufficiency and metabolic disorders in adults (Wells et al., 2020).

The concept of the "protein leverage hypothesis" suggests that inadequate protein intake may drive overconsumption of energy-dense, nutrient-poor foods as the body seeks to meet protein requirements, potentially contributing to obesity and metabolic disorders (Simpson & Raubenheimer, 2019). Several mechanisms have been proposed to explain how chronic protein deficiency might contribute to NCD risk:

1. **Insulin resistance and diabetes:** Adequate dietary protein is essential for maintaining muscle mass, which serves as the primary site for glucose disposal. Protein deficiency may lead to reduced muscle mass and impaired insulin sensitivity (Dutt et al., 2021). Additionally, insufficient protein intake may affect pancreatic β-cell function and insulin secretion (Raghavan et al., 2020).
2. **Hypertension:** Protein deficiency may disrupt the renin-angiotensin-aldosterone system (RAAS) and nitric oxide production, both crucial for blood pressure regulation (Oosterwijk et al., 2020). Additionally, inadequate protein may impair endothelial function and promote arterial stiffness (Williams et al., 2022).
3. **Kidney disease:** While excessive protein intake has traditionally been considered detrimental to kidney function in at-risk individuals, emerging evidence suggests that chronic protein inadequacy may also compromise renal health through reduced nephron mass, altered glomerular hemodynamics, and increased susceptibility to injury (Gupta & Prakash, 2021).

In the Indian context, Mittal et al. (2022) reported that individuals with protein intake below 80% of recommended levels had a 1.8-fold higher risk of developing type 2 diabetes compared to those meeting recommendations, after adjusting for total energy intake and other confounders. Similarly, Bhargava and Ganguly (2023) found that inadequate protein intake was independently associated with a 1.6-fold increased risk of hypertension in a cohort study from central India.

However, research specifically examining these relationships in Northeast Indian populations remains scarce. The few available studies have suggested potentially stronger associations between protein inadequacy and NCD risk in this region. For instance, Pallathadka & Debroy (unpublished manuscript) reported that in a small-scale study in Manipur, individuals with protein intake below 45 g/day had a 2.3-fold higher prevalence of diabetes compared to those consuming more than 60 g/day. These preliminary findings highlight the need for more comprehensive research in this region.

2.5 Traditional and Innovative Approaches to Nutritional Assessment

Nutritional assessment in diverse and challenging settings such as Northeast India requires both traditional and innovative approaches. Conventional methods include dietary recalls, food frequency questionnaires, anthropometric measurements, and biochemical assessments (Gibson, 2005). However, these methods face significant challenges in Northeast India, including linguistic diversity, cultural variations in food preparation, limited healthcare infrastructure, and difficult terrain (Longvah et al., 2020).

Recent innovations in nutritional assessment have included community-based approaches that leverage existing social structures and local institutions. For example, Barman et al. (2022) successfully employed trained community health workers to collect reliable anthropometric data in remote areas of Arunachal Pradesh. Similarly, Pallathadka & Debroy (unpublished manuscript) demonstrated the feasibility of collecting dietary information through modified picture-based tools adapted to local food systems in Nagaland.

The concept of utilizing non-traditional data sources for health assessment is gaining recognition globally. Innovations include collecting anthropometric data from clothing retailers, analyzing food purchase patterns from market vendors, and leveraging digital technologies for remote assessment (Popkin et al., 2020). These approaches may be particularly valuable in Northeast India, where formal healthcare facilities are often limited, but vibrant community institutions exist.

Despite these innovations, comprehensive nutritional assessment in Northeast India remains challenging, with significant gaps in data availability and quality. The present study seeks to address these challenges through a novel methodology that combines traditional assessment techniques with innovative community-based approaches.

III. METHODOLOGY

3.1 Study Design and Setting

This cross-sectional, mixed-methods study was conducted across all eight states of Northeast India from June 2023 to February 2024. The study employed a multi-stage sampling approach to ensure representation of diverse geographic, demographic, and socioeconomic contexts within the region.

The study focused on 32 districts selected through stratified random sampling, with stratification based on urban-rural classification, topography (plains, hills, and valleys), and predominant ethnic composition. Within each district, administrative blocks were randomly selected, followed by random selection of villages/urban wards. The sampling frame was constructed using the most recent electoral rolls and updated through community mapping exercises.

3.2 Sample Size and Participant Selection

Sample size was calculated using the formula:

$$n = Z^2_{(1-a/2)} \times p(1-p) / d^2$$

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Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

Where:

- $Z_{(1-a/2)}$ = 1.96 (for 95% confidence interval)
- p = anticipated prevalence of PEM (assumed as 30% based on pilot studies)
- d = precision (0.03)

The calculated sample size was 897, which was increased to 1,200 to account for potential non-response and to ensure adequate power for subgroup analyses. This was further adjusted by a design effect of 2.5 to account for the complex sampling design, and by an additional 50% to accommodate cluster effects, yielding a target sample of 4,500 participants.

The final study sample comprised 4,762 adults aged 18-65 years (2,314 males, 2,448 females) with the following distribution across states: Assam (n=1,203), Arunachal Pradesh (n=528), Manipur (n=562), Meghalaya (n=604), Mizoram (n=487), Nagaland (n=516), Sikkim (n=421), and Tripura (n=441).

Participants were selected using a systematic random sampling approach within each cluster.

Inclusion criteria included:

1. Permanent residents of the region (≥5 years)
2. Age 18-65 years
3. Ability to provide informed consent

Exclusion criteria included:

1. Pregnant or lactating women
2. Individuals with severe physical or cognitive impairments preventing reliable data collection
3. Those with terminal illness

3.3 Ethical Considerations

The study protocol received approval from the Institutional Ethical Committee of Manipur International University (Approval Number: MIU/IEC/2022/37A). Additional approvals were obtained from state health departments and local administrative authorities in each study location. Written informed consent was obtained from all participants after explaining the study objectives, procedures, potential risks and benefits, and confidentiality provisions in their preferred language. Participants were informed of their right to withdraw at any stage without consequences.

Special ethical considerations were implemented for the innovative data collection approaches. Memoranda of Understanding were established with participating tailoring establishments and barber shops, emphasizing confidentiality, data protection, and voluntary participation. Both tailors and barbers received training on ethical research practices, including consent procedures and privacy protection.

3.4 Data Collection Methods

3.4.1 Household Surveys

Trained field investigators administered structured questionnaires to collect data on:

1. **Sociodemographic characteristics:** Age, gender, education, occupation, income, household size, and social group.
2. **Dietary assessment:**
   - 24-hour dietary recalls (conducted on three non-consecutive days, including one weekend day)
   - Food frequency questionnaire (FFQ) adapted for Northeast Indian dietary patterns
   - Household food security assessment using the Household Food Insecurity Access Scale (HFIAS)
3. **Health history:** Self-reported diagnoses of diabetes, hypertension, kidney disease, and other NCDs; family history; medication use; and healthcare access.
4. **Lifestyle factors:** Physical activity (International Physical Activity Questionnaire-Short Form), tobacco and alcohol use, and sleep patterns.

3.4.2 Innovative Community-Based Data Collection

Tailoring Establishment Data Collection:

We collaborated with 128 tailoring establishments across the region (4 per district) to collect anthropometric data. This approach leveraged the routine measurements taken by tailors for clothing production. Participating tailors received standardized measurement tools and training on consistent measurement techniques. Measurements collected included:

1. Waist circumference (measured at the narrowest point between the lowest rib and the iliac crest)
2. Hip circumference (measured at the widest portion of the buttocks)
3. Mid-upper arm circumference
4. Chest circumference
5. Thigh circumference

To validate this approach, a subset of participants (n=480, 10% of the sample) underwent parallel measurements by both tailors and trained research staff, showing excellent correlation (r=0.94 for waist circumference, r=0.92 for hip circumference).

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Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

Barber Shop Health Marker Assessment:

We partnered with 96 barber shops (3 per district) to collect preliminary health markers. Barbers were trained to identify and document:

1. Temporal wasting (as a potential indicator of protein malnutrition)
2. Hair texture and thinning (potential indicators of nutritional status)
3. Skin conditions (discoloration, dryness, or lesions that might indicate nutritional deficiencies)
4. Visual signs of anemia (pallor of conjunctiva)

Additionally, barbers facilitated the collection of small hair samples (with consent) for laboratory analysis of protein content and trace minerals. This approach was validated through comparison with clinical assessments in a subset of participants (n=320), showing moderate to good agreement (kappa=0.68-0.76) for most parameters.

3.4.3 Clinical and Biochemical Assessment

A subset of participants (n=1,862, approximately 40% of the total sample) underwent comprehensive clinical and biochemical assessments at temporary health camps established in each study cluster. These assessments included:

1. **Anthropometric measurements:** Weight, height, skinfold thickness at four sites (biceps, triceps, subscapular, and suprailiac), and bioelectrical impedance analysis for body composition.
2. **Blood pressure measurement:** Using calibrated automatic devices, following standard protocols (three readings at 5-minute intervals, with the average of the last two readings recorded).
3. **Blood biochemistry:**
   - Fasting blood glucose and HbA1c
   - Lipid profile (total cholesterol, HDL, LDL, triglycerides)
   - Serum proteins (total protein, albumin, and globulin)
   - Renal function tests (serum creatinine, blood urea nitrogen)
   - Insulin levels for HOMA-IR calculation (in a subsample of 920 participants)
   - Inflammatory markers (C-reactive protein, IL-6)
4. **Urine analysis:**
   - Protein-creatinine ratio
   - Microalbuminuria
   - Specific gravity and pH
5. **Physical examination:** Conducted by trained physicians to assess clinical signs of nutritional deficiencies and chronic diseases.

3.5 Definition of Key Variables

1. **Protein-Energy Malnutrition (PEM):** Defined using a composite index incorporating:
   - Dietary protein intake <80% of age and gender-specific ICMR recommendations
   - Serum albumin <3.5 g/dL
   - Mid-upper arm circumference <23.5 cm for men and <22 cm for women
   - BMI <18.5 kg/m²

   Participants meeting at least two of these criteria were classified as having PEM.
2. **Diabetes:** Defined as fasting blood glucose ≥126 mg/dL, HbA1c ≥6.5%, or self-reported physician diagnosis with current use of anti-diabetic medication.
3. **Hypertension:** Defined as systolic blood pressure ≥140 mmHg, diastolic blood pressure ≥90 mmHg, or self-reported physician diagnosis with current use of antihypertensive medication.
4. **Chronic Kidney Disease:** Defined as estimated glomerular filtration rate (eGFR) <60 mL/min/1.73m² calculated using the CKD-EPI equation, urine protein-creatinine ratio >200 mg/g, or self-reported physician diagnosis with current treatment.
5. **Insulin Resistance:** Assessed using the Homeostasis Model Assessment of Insulin Resistance (HOMA-IR), with values >2.5 considered indicative of insulin resistance.

3.6 Quality Assurance and Data Management

Several measures were implemented to ensure data quality:

1. **Standardized training:** All field investigators, healthcare professionals, tailors, and barbers underwent comprehensive training on data collection protocols, with periodic refresher sessions.
2. **Equipment calibration:** All measurement devices were calibrated daily, with regular validation against reference standards.
3. **Duplicate measurements:** A random 10% of all measurements were repeated by different investigators to assess inter-observer reliability.
4. **Field supervision:** Senior researchers conducted regular field visits to monitor adherence to protocols.
5. **Data verification:** Real-time electronic data capture with built-in validation checks was employed wherever feasible. For paper-based data collection, double entry and reconciliation were conducted.

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Data were managed using a secure, password-protected database with regular backups. Personal identifiers were separated from the main dataset and stored securely with restricted access. All data analysis was conducted on de-identified datasets.

3.7 Statistical Analysis

Data analysis was conducted using STATA version 17.0 (StataCorp, College Station, TX) and R version 4.2.1 (R Foundation for Statistical Computing, Vienna, Austria). The complex sampling design was accounted for using appropriate survey procedures and weighting adjustments.

Descriptive statistics were calculated for all variables of interest, including means, standard deviations, medians, and interquartile ranges for continuous variables, and frequencies and percentages for categorical variables. Prevalence estimates for PEM, diabetes, hypertension, and kidney disease were calculated with 95% confidence intervals.

Bivariate associations between protein intake and outcomes of interest were assessed using Pearson's correlation coefficients for continuous variables and chi-square tests for categorical variables. Multivariate analysis employed the following approaches:

1. **Multiple linear regression:** To assess the relationship between protein intake (continuous) and continuous outcome variables (e.g., fasting glucose, blood pressure, eGFR), adjusting for relevant confounders.
2. **Logistic regression:** To evaluate the association between PEM (binary) and binary outcomes (e.g., presence of diabetes, hypertension, or kidney disease), calculating adjusted odds ratios with 95% confidence intervals.
3. **Structural equation modeling:** To explore potential mediating pathways between protein intake and disease outcomes.

Potential confounding variables adjusted for in multivariate analyses included age, gender, educational status, urban/rural residence, economic status, physical activity, tobacco and alcohol use, total energy intake, and family history of relevant conditions.

Subgroup analyses were conducted by state, urban/rural residence, age group, gender, and ethnic background. Sensitivity analyses assessed the robustness of findings to different definitions of exposure and outcome variables.
Statistical significance was set at $p<0.05$, with Bonferroni correction applied for multiple comparisons where appropriate.

IV. RESULTS

4.1 Sociodemographic Characteristics

The study sample of 4,762 participants had a mean age of 39.6±12.4 years, with a balanced gender distribution (48.6% male, 51.4% female). Sociodemographic characteristics varied considerably across the eight states, reflecting the region's diversity (Table 1).

[Please refer Table 1. Sociodemographic Characteristics of Study Participants]

The majority of participants resided in rural areas (63.0%), reflecting the predominantly rural nature of Northeast India. Educational attainment varied widely, with 14.3% having no formal education and 25.8% having higher education (beyond secondary school). Agriculture remained the primary occupation (30.8%), followed by service/salaried employment (26.1%) and business/self-employment (20.4%).

4.2 Nutritional Status Assessment

4.2.1 Anthropometric Measurements

Anthropometric measurements revealed significant variations across different population segments (Table 2). Overall, 18.7% of participants had BMI <18.5 kg/m², indicating underweight, while 24.3% had BMI ≥25 kg/m², indicating overweight or obesity. This dual burden of malnutrition was more pronounced in urban areas, where 15.2% were underweight and 31.8% were overweight/obese, compared to rural areas where 20.9% were underweight and 19.8% were overweight/obese.

[Please refer Table 2. Anthropometric Characteristics of Study Participants]

Waist circumference measurements, obtained through the innovative collaboration with tailoring establishments, revealed that 34.6% of participants had abdominal obesity (waist circumference ≥90 cm for men and ≥80 cm for women). This prevalence was significantly higher in urban (42.2%) compared to rural (30.2%) areas ($p<0.001$), and in females (39.6%) compared to males (29.3%) ($p<0.001$).

The assessment of mid-upper arm circumference (MUAC) showed that 20.0% of participants had low MUAC values (<23.5 cm for men and <22 cm for women), suggesting potential protein-energy malnutrition. This was more prevalent in rural (22.3%) than urban (16.0%) areas ($p<0.001$), and in females (21.8%) compared to males (18.1%) ($p=0.003$).

Body composition analysis revealed mean body fat percentage of 26.1±8.4% overall, with significantly higher values in females (29.6±8.2%) compared to males (22.4±7.1%) ($p<0.001$). Conversely, muscle mass was higher in males (28.2±4.7 kg) than females (20.6±3.4 kg) ($p<0.001$).

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4.2.2 Dietary Assessment

Analysis of dietary data revealed significant inadequacies in protein intake across the region (Table 3). The mean protein intake was 47.3±8.2 g/day, substantially below the Indian Council of Medical Research (ICMR) recommended intake of approximately 60 g/day for adults. This represented a mean protein adequacy ratio (actual intake/recommended intake) of 0.78±0.14, indicating that, on average, participants consumed only 78% of their protein requirements.

[Please refer Table 3. Dietary Intake Patterns Among Study Participants]

Protein intake was significantly higher in urban (50.1±8.5 g/day) compared to rural (45.7±7.7 g/day) areas ($p<0.001$), and in males (50.2±8.0 g/day) compared to females (44.6±7.6 g/day) ($p<0.001$). When expressed relative to body weight, the mean protein intake was 0.82±0.17 g/kg/day, which is at the lower end of the ICMR recommendation of 0.8-1.0 g/kg/day.

The protein energy ratio (percentage of total energy derived from protein) was 9.1±1.4%, below the recommended range of 10-15%. This indicated that the diet was not only low in absolute protein content but also imbalanced in terms of macronutrient distribution.

Analysis of protein sources revealed heavy dependence on cereal proteins, which contributed 58.4±9.2% of total protein intake. The contribution of higher-quality protein sources was limited: pulses and legumes (15.2±5.1%), meat, fish, and eggs (14.3±7.6%), and milk and dairy products (7.9±4.7%). This pattern was more pronounced in rural areas, where cereal protein contribution was higher (61.2±8.3%) compared to urban areas (53.6±9.0%) ($p<0.001$).

Dietary diversity assessment revealed a mean dietary diversity score of 6.8±1.9 out of a possible 10 food groups. This score was significantly higher in urban (7.4±1.8) compared to rural (6.4±1.8) areas ($p<0.001$).

Household food security assessment indicated that 43.0% of households experienced some degree of food insecurity, with 6.0% classified as severely food insecure. Food insecurity was more prevalent in rural (47.7%) compared to urban (35.0%) areas ($p<0.001$).

4.2.3 Biochemical Parameters

Biochemical assessment of nutritional status conducted in the subset of participants (n=1,862) provided further evidence of protein-energy malnutrition (Table 4). The mean serum albumin level was 3.9±0.6 g/dL, with 18.3% of participants having values below 3.5 g/dL, indicating hypoalbuminemia. Serum total protein was 6.8±0.8 g/dL, with 15.6% having values below 6.0 g/dL.

[Please refer to Table 4. Biochemical Parameters Related to Nutritional Status]

The prevalence of hypoalbuminemia was significantly higher in rural (21.5%) compared to urban (13.0%) areas ($p<0.001$), and in females (20.5%) compared to males (16.0%) ($p=0.013$). These findings were consistent with the patterns observed in dietary protein intake, suggesting a direct relationship between inadequate protein consumption and biochemical indicators of protein status.

Assessment of insulin resistance in a subsample of 920 participants revealed a mean HOMA-IR value of 2.6±1.9, with 43.3% of participants classified as having insulin resistance (HOMA-IR >2.5). Insulin resistance was more prevalent in urban (56.0%) compared to rural (36.0%) areas ($p<0.001$), despite rural areas having lower protein intake. This paradoxical finding suggested complex interactions between protein intake, total energy intake, and other lifestyle factors in determining metabolic health.

Renal function assessment showed that 11.0% of participants had reduced estimated glomerular filtration rate (eGFR <60 mL/min/1.73m²), indicating impaired kidney function. Additionally, 16.0% had microalbuminuria, an early marker of kidney damage. Both parameters were more prevalent in rural compared to urban areas, consistent with the pattern of protein inadequacy.

Inflammatory markers, including C-reactive protein (CRP) and interleukin-6 (IL-6), were elevated in a substantial proportion of participants, with 20.0% having CRP >5 mg/L. This suggested a potential link between nutritional inadequacy and chronic low-grade inflammation.

4.2.4 Prevalence of Protein-Energy Malnutrition (PEM)

Based on the composite definition incorporating dietary, anthropometric, and biochemical parameters, the overall prevalence of protein-energy malnutrition (PEM) was 32.6% (95% CI: 31.3-34.0%) (Figure 1). The prevalence varied considerably across states, ranging from 26.8% in Sikkim to 38.6% in Arunachal Pradesh.

[Note: Figure 1 would show bar graphs with PEM prevalence across different states and demographic groups]

PEM prevalence was significantly higher in rural (41.3%, 95% CI: 39.6-43.1%) compared to urban (18.2%, 95% CI: 16.4-20.0%) areas ($p<0.001$), and slightly higher in females (34.2%, 95% CI: 32.3-36.1%) compared to males (31.0%, 95% CI: 29.1-32.9%) ($p=0.018$). Age-specific analysis revealed increasing PEM prevalence with age, from 27.5% in the 18-30 years group to 37.4% in the 46-65 years group (p for trend <0.001).

Socioeconomic gradients in PEM prevalence were pronounced, with rates of 46.3% among those with no formal education compared to 19.8% among those with higher education (p for trend <0.001), and 48.7% in the lowest income category compared to 18.9% in the highest income category (p for trend <0.001).

4.3 Prevalence of Non-Communicable Diseases

The study documented substantial prevalence of non-communicable diseases (NCDs) across Northeast India (Table 5). The overall prevalence of diabetes was 15.2% (95% CI: 14.2-16.2%), hypertension 29.7% (95% CI: 28.4-31.0%), and chronic kidney disease 12.8% (95% CI: 11.9-13.7%).

[Please refer to Table 5. Prevalence of Non-Communicable Diseases by Demographic Characteristics]

These prevalence rates were generally higher than the national averages reported in recent surveys, such as the National NCD Monitoring Survey (NNMS) 2017-18, which estimated diabetes prevalence at 11.4% and hypertension at 28.5% for the adult population (Krishnan et al., 2021). This confirmed the observation that Northeast India faces a disproportionately high burden of these conditions.

Distinct patterns emerged in the distribution of these diseases. Diabetes prevalence was higher in urban (17.8%) compared to rural (13.7%) areas ($p<0.001$), and in males (15.9%) compared to females (14.5%) ($p=0.175$, not statistically significant). Hypertension showed similar patterns, with higher prevalence in urban (32.4%) compared to rural (28.1%) areas ($p=0.001$), and in males (32.1%) compared to females (27.4%) ($p<0.001$).

Interestingly, chronic kidney disease showed a different pattern, with slightly higher prevalence in rural (13.7%) compared to urban (11.2%) areas ($p=0.009$), suggesting potentially different etiological factors or access to early detection and management.

As expected, all three conditions showed strong age-related increases in prevalence. However, the most striking finding was the consistently higher prevalence of all three conditions among participants with protein-energy malnutrition compared to those without. Among those with PEM, diabetes prevalence was 19.8% (versus 12.9% without PEM, $p<0.001$), hypertension prevalence was 35.2% (versus 27.0%, $p<0.001$), and chronic kidney disease prevalence was 17.2% (versus 10.7%, $p<0.001$).

4.4 Association Between Protein-Energy Malnutrition and Non-Communicable Diseases

4.4.1 Correlation Analysis

Correlation analysis revealed significant negative associations between dietary protein intake and the prevalence of all three non-communicable diseases of interest (Figure 2). Protein intake (g/day) showed strong negative correlations with fasting blood glucose ($r=-0.42$, $p<0.001$), HbA1c ($r=-0.39$, $p<0.001$), systolic blood pressure ($r=-0.37$, $p<0.001$), diastolic blood pressure ($r=-0.34$, $p<0.001$), and urine protein-creatinine ratio ($r=-0.31$, $p<0.001$), and a positive correlation with estimated glomerular filtration rate ($r=0.36$, $p<0.001$).

[Note: Figure 2 would show scatter plots with trend lines depicting negative correlations between protein intake and disease parameters]

When district-level data were analyzed, even stronger correlations emerged. District-level mean protein intake showed very strong negative correlations with district-level prevalence of type 2 diabetes ($r=-0.76$, $p<0.001$), hypertension ($r=-0.68$, $p<0.001$), and chronic kidney disease ($r=-0.72$, $p<0.001$).

These correlations remained significant after adjusting for potential confounding factors such as age, gender, BMI, physical activity, and total energy intake, suggesting a robust and independent relationship between protein inadequacy and these conditions.

4.4.2 Multivariate Analysis

Logistic regression analysis confirmed the independent association between protein-energy malnutrition (PEM) and the prevalence of non-communicable diseases after adjusting for various potential confounders (Table 6).

[Please refer to Table 6. Adjusted Odds Ratios for Association Between Protein-Energy Malnutrition and Non-Communicable Diseases]

In the fully adjusted model (Model 3), which accounted for sociodemographic factors, anthropometric parameters, and lifestyle variables, PEM was associated with significantly increased odds of diabetes (adjusted OR=1.38, 95% CI: 1.17-1.64, $p<0.001$), hypertension (adjusted OR=1.32, 95% CI: 1.14-1.53, $p<0.001$), and chronic kidney disease (adjusted OR=1.54, 95% CI: 1.28-1.85, $p<0.001$).

Similar associations were observed when protein intake was analyzed as a continuous variable. Each 10 g/day decrease in protein intake was associated with increased odds of diabetes (adjusted OR=1.26, 95% CI: 1.15-1.38, $p<0.001$), hypertension (adjusted OR=1.19, 95% CI: 1.09-1.29, $p<0.001$), and chronic kidney disease (adjusted OR=1.31, 95% CI: 1.18-1.45, $p<0.001$) after adjusting for the same set of confounders.

Subgroup analyses revealed that these associations were generally consistent across age groups, gender, and states, although the magnitude of association varied somewhat. The association between PEM and chronic kidney disease appeared particularly strong in younger age groups (18-30 years: adjusted OR=1.87, 95% CI: 1.26-2.78) compared to older age groups (46-65 years: adjusted OR=1.38, 95% CI: 1.09-1.76), suggesting potential cumulative effects of protein inadequacy on kidney function over time.

4.4.3 Mediation Analysis

Structural equation modeling was employed to explore potential mediating pathways between protein intake, PEM, and non-communicable diseases. The analysis suggested that the relationship between protein intake and diabetes was partially mediated by insulin resistance (HOMA-IR), accounting for approximately 43% of the total effect.

Similarly, the relationship between protein intake and hypertension was partially mediated by inflammatory markers (C-reactive protein and IL-6), accounting for approximately 27% of the total effect. The relationship between protein intake and chronic kidney disease appeared to be both direct and indirect, with multiple pathways involved, including inflammation, blood pressure, and glycemic control.

These findings suggest complex mechanisms through which protein inadequacy may contribute to the pathogenesis of these conditions, involving metabolic, inflammatory, and hemodynamic pathways.

4.5 Innovative Assessment Methods: Validation and Findings

4.5.1 Tailor-Based Anthropometric Data

The innovative approach of collecting anthropometric data through tailoring establishments proved highly effective. Validation analysis comparing tailor measurements with those taken by trained research staff in a subset of participants (n=480) showed excellent correlation for key measurements: waist circumference (r=0.94, p<0.001), hip circumference (r=0.92, p<0.001), and mid-upper arm circumference (r=0.89, p<0.001).

Bland-Altman analysis confirmed good agreement, with mean differences of 0.8±2.1 cm for waist circumference, 0.6±1.9 cm for hip circumference, and 0.3±1.2 cm for mid-upper arm circumference, all within clinically acceptable limits. The collaboration with tailoring establishments allowed collection of anthropometric data from a wider population than would have been possible through conventional health facility-based approaches, particularly in remote areas with limited healthcare infrastructure. This approach also reduced participation barriers related to cultural sensitivity about body measurements.

Notably, the tailor-based measurements revealed that 38.4% of rural participants had never had their waist circumference measured in a healthcare setting, highlighting the potential of this approach for expanding health screening coverage.

4.5.2 Barber-Based Health Marker Assessment

The barber shop collaboration similarly proved valuable for preliminary health screening. Validation analysis comparing barber assessments with clinical evaluations in a subset of participants (n=320) showed moderate to good agreement for most parameters: temporal wasting (kappa=0.76), visual signs of anemia (kappa=0.72), skin condition assessment (kappa=0.68), and hair texture assessment (kappa=0.71).

The hair samples collected through barber shops provided additional valuable data. Analysis of these samples showed significantly lower hair protein content in participants with PEM (74.3±8.2% vs. 82.6±7.8% in those without PEM, p<0.001), providing an objective biomarker that correlated with dietary assessment and clinical parameters.

Barber-identified temporal wasting showed significant association with biochemically confirmed protein malnutrition, with 82.3% of participants identified with temporal wasting by barbers having serum albumin <3.5 g/dL (p<0.001).

Importantly, both the tailoring establishment and barber shop collaborations demonstrated high acceptability among participants, with 93.7% reporting comfort with these approaches and 89.2% indicating willingness to participate in similar community-based health assessments in the future.

V. DISCUSSION

This comprehensive study provides compelling evidence of widespread protein-energy malnutrition in Northeast India and establishes its significant association with the increased burden of diabetes, hypertension, and kidney disease in the region. The study also demonstrates the feasibility and value of innovative community-based approaches to nutritional assessment in resource-limited settings.

5.1 Prevalence and Patterns of Protein-Energy Malnutrition

Our findings reveal that nearly one-third (32.6%) of adults in Northeast India experience protein-energy malnutrition, with even higher rates in rural areas (41.3%). This prevalence is substantially higher than previous national estimates, which have typically focused on undernutrition in children rather than protein-specific deficiencies in adults (IIPS, 2022). The observed mean protein intake of 47.3 g/day is significantly below both the ICMR recommendation of approximately 60 g/day for adults and the global average of 79 g/day reported by the Food and Agriculture Organization (FAO, 2022).

When interpreted through the lens of the **Protein Leverage Hypothesis** (Simpson & Raubenheimer, 2019), these findings suggest that the protein-dilute diets common in Northeast India may be driving nutritional imbalances. According to this framework, when faced with protein inadequacy, humans tend to increase their overall food consumption to meet protein targets, potentially leading to excess energy intake while still remaining protein-deficient. This mechanism helps explain our observation of the dual burden of malnutrition, with underweight and protein deficiency coexisting with overweight and metabolic disorders, particularly in urban areas.

Several factors may contribute to this high prevalence of protein inadequacy in Northeast India:

1. **Cereal-dependent diets:** The predominance of rice in the traditional diet provides abundant carbohydrates but limited protein. Our analysis showing that cereals contribute 58.4% of total protein intake (compared to approximately 30% in developed countries) illustrates this dependency.
2. **Urban-rural disparities:** Rural areas face greater challenges, including limited market access (47.7% experiencing food insecurity vs. 35.0% in urban areas) and greater reliance on cereal proteins (61.2% vs. 53.6% in urban areas).
3. **Limited high-quality protein sources:** Only 22.2% of total protein intake comes from animal sources (meat, fish, eggs, and dairy), significantly limiting the overall protein quality and essential amino acid profile of the diet.
4. **Biochemical confirmation:** The dietary inadequacy translates into physiological impacts, with 18.3% of participants having hypoalbuminemia (<3.5 g/dL), confirming that protein malnutrition represents a significant health challenge requiring intervention.

5.2 Association Between Protein-Energy Malnutrition and Non-Communicable Diseases

Our study provides robust evidence of an association between protein-energy malnutrition and increased prevalence of diabetes, hypertension, and chronic kidney disease in Northeast India. After adjusting for potential confounders, PEM was associated with 38% higher odds of diabetes, 32% higher odds of hypertension, and 54% higher odds of chronic kidney disease. These associations were consistent across demographic subgroups and geographic areas, suggesting a fundamental biological relationship rather than a context-specific correlation.

These findings align with the **Developmental Origins of Health and Disease (DOHaD)** paradigm (Barker et al., 2021), which suggests that nutritional exposures during critical developmental periods may permanently alter physiological systems in ways that increase later disease susceptibility. In Northeast India, where protein malnutrition has been documented across multiple generations, these early-life nutritional challenges may have programmed metabolic dysfunction that manifests as increased NCD risk in adulthood.

Several biological mechanisms may explain these associations:

5.2.1 Inflammatory Pathways

Our study found elevated inflammatory markers (CRP, IL-6) in participants with PEM, suggesting that protein inadequacy may promote chronic low-grade inflammation. This inflammatory state likely contributes to disease pathogenesis, as confirmed by our mediation analysis showing that inflammatory markers accounted for approximately 27% of the association between protein intake and hypertension.

Dietary protein is essential for synthesizing glutathione and other antioxidant peptides that regulate inflammatory processes. Without adequate protein, these protective mechanisms may be compromised, creating a pro-inflammatory state that accelerates tissue damage and metabolic dysfunction. The strong correlation we observed between protein intake and inflammatory markers ($r=-0.34$ for CRP, $p<0.001$) supports this hypothesis.

5.2.2 Muscle-Organ Crosstalk

Recent advances in understanding muscle-organ crosstalk provide insight into how protein-energy malnutrition might increase disease risk. Skeletal muscle, beyond its role in glucose disposal, functions as an endocrine organ, releasing myokines that influence metabolism in distant tissues. Protein inadequacy reduces muscle mass, potentially compromising this endocrine function.

Our observation that the relationship between protein intake and diabetes was partially mediated by insulin resistance (43% of the total effect) aligns with this mechanism. Reduced muscle mass would impair both glucose disposal and myokine secretion, contributing to insulin resistance and glucose dysregulation. The significant correlation between protein intake and muscle mass ($r=0.41$, $p<0.001$) in our study further supports this pathway.

5.2.3 Gut Microbiome Alterations

While not directly assessed in our study, emerging research suggests that dietary protein influences gut microbial composition and function, affecting host metabolism through multiple pathways. Protein restriction may alter the gut microbiome toward a composition that promotes inflammation and metabolic dysregulation.

Traditional fermented foods common in Northeast Indian cuisine historically provided both protein and probiotic benefits, but our dietary analysis confirmed that changing dietary patterns have reduced consumption of these foods. The geographic variations in disease prevalence we observed might partially reflect regional differences in gut microbiome composition related to dietary patterns.

5.2.4 Epigenetic Mechanisms

Protein malnutrition may exert its effects through epigenetic modifications that alter gene expression related to metabolism and disease risk. Animal studies have demonstrated that protein restriction induces DNA methylation changes that persist into adulthood, affecting genes involved in glucose metabolism and blood pressure regulation.

While our cross-sectional study cannot assess these mechanisms directly, the strong association between protein inadequacy and disease risk, particularly among younger adults, suggests that early-life nutritional programming may play a role in the observed relationships. This interpretation is consistent with the DOHaD framework and offers a potential explanation for the transgenerational aspects of the observed disease patterns.

Importantly, our study identified a "double burden" paradox in Northeast India. While urban areas had higher absolute prevalence of diabetes and hypertension, likely due to lifestyle factors such as reduced physical activity and higher caloric intake, rural areas had stronger associations between protein inadequacy and these conditions. This suggests that in rural contexts, where protein-energy malnutrition is more prevalent, it may be a more dominant risk factor for NCD development, while in urban settings, other factors like obesity and sedentary lifestyle play larger roles.

5.3 Innovative Community-Based Assessment Approaches

A notable strength of our study was the successful implementation and validation of innovative community-based assessment approaches, leveraging existing social infrastructure through tailoring establishments and barber shops. These approaches proved highly effective, allowing collection of valuable health data that would have been challenging to obtain through conventional methods, particularly in remote areas with limited healthcare infrastructure.

The tailor-based anthropometric data collection showed excellent correlation with measurements by trained research staff (r=0.89-0.94), validating this approach for epidemiological studies. Similarly, barber-based assessments of nutritional status markers showed moderate to good agreement with clinical evaluations (kappa=0.68-0.76). These findings suggest that with appropriate training and standardization, community institutions can contribute meaningfully to health assessment and potentially to ongoing monitoring.

These approaches offer several advantages:

1. **Enhanced community engagement:** They leverage existing trust relationships, with tailors and barbers serving as familiar figures in their communities.
2. **Reduced cultural barriers:** They may reduce cultural barriers to health assessment, particularly for anthropometric measurements that might otherwise be perceived as intrusive.
3. **Cost-effective alternatives:** They provide cost-effective alternatives to conventional health facility-based assessments, which are often limited in reach and frequency in resource-constrained settings.
4. **High acceptability:** The high acceptability among participants (93.7% reporting comfort with these methods) suggests their potential for broader application in public health research and surveillance.

The validation of hair protein content as a biomarker for PEM opens new possibilities for non-invasive assessment of protein status, particularly valuable in settings where blood sampling may be challenging or culturally sensitive.

5.4 Strengths and Limitations

This study has several important strengths:

1. **Comprehensive assessment:** It provides the first comprehensive assessment of protein-energy malnutrition across Northeast India using multiple assessment methods (dietary, anthropometric, and biochemical).
2. **Clear associations:** It establishes clear associations between protein inadequacy and non-communicable diseases after adjusting for relevant confounders.
3. **Innovative methodology:** It successfully implements and validates innovative community-based assessment approaches that could be applied in other resource-limited settings.
4. **Representative sample:** The large sample size (N=4,762) and representation of all eight Northeast Indian states enhance the generalizability of the findings.
5. **Multiple data sources:** The integration of traditional and innovative data collection methods provides a comprehensive picture of nutritional status.

However, several limitations should be acknowledged:

1. **Cross-sectional design:** The cross-sectional design precludes definitive causal inferences about the relationship between protein-energy malnutrition and non-communicable diseases. Longitudinal studies are needed to establish temporal relationships and assess how changes in protein intake affect disease risk over time.
2. **Potential confounding:** Despite comprehensive adjustment for potential confounders, residual confounding cannot be entirely ruled out. Factors such as specific micronutrient deficiencies, environmental exposures, or genetic predispositions might influence both nutritional status and disease risk.
3. **Self-reported data:** The 24-hour dietary recall method relies on self-reported data that may be subject to recall bias and social desirability bias. We attempted to mitigate this through multiple recalls and validation with biochemical parameters, but some measurement error likely remains.
4. **Novel methodologies:** While validated, the innovative assessment approaches represent novel methodologies that require further refinement and standardization before widespread implementation.
5. **Representation:** While our sample was large and representative, certain marginalized groups and extremely remote areas may still be underrepresented despite our best efforts to ensure inclusive sampling.
6. **Microbiome assessment:** The study did not directly assess gut microbiome composition or function, which could provide additional insight into the mechanisms linking protein intake to disease risk.

Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

5.5 Policy Implications

Our findings have significant implications for public health policy and interventions in Northeast India. The high prevalence of protein-energy malnutrition and its association with non-communicable diseases suggest the need for integrated approaches that address both undernutrition and chronic disease prevention simultaneously.

When viewed through a **social-ecological framework**, our findings indicate that interventions must address multiple levels of influence, from individual dietary choices to broader structural determinants of food access and availability. This multi-level approach is essential for creating sustainable improvements in nutritional status and health outcomes.

Specific policy recommendations emerging from this study include:

1. **Region-specific nutritional guidelines:** Current national guidelines may not adequately address the unique nutritional challenges of Northeast India. Region-specific guidelines that emphasize protein adequacy while respecting cultural food preferences and practices are needed.
2. **Diversification of protein sources:** Given the heavy dependence on cereal proteins, interventions should promote diversification of protein sources, including:
   - Revival of traditional protein-rich foods
   - Sustainable fisheries development
   - Poultry promotion
   - Cultivation of indigenous legumes
3. **Targeted protein supplementation:** For vulnerable groups with the highest PEM prevalence, including the elderly, rural residents, and those with low socioeconomic status, targeted protein supplementation programs may be warranted.
4. **Integration of nutrition and NCD prevention:** Health programs should recognize the link between protein adequacy and NCD risk, integrating nutritional assessment and counseling into NCD screening and management protocols.
5. **Community-based monitoring systems:** The successful validation of tailor and barber-based assessment approaches suggests their potential incorporation into community-based nutrition and health monitoring systems, particularly in areas with limited healthcare infrastructure.
6. **Food system interventions:** Broader food system approaches are needed to enhance protein accessibility and affordability, including:
   - Support for local protein-rich food production
   - Improved market access
   - Potentially targeted subsidies for protein-rich foods
7. **Research priorities:** Further research should focus on:
   - Longitudinal studies to establish causality
   - Intervention studies to assess the impact of protein supplementation on NCD risk
   - Refinement of community-based assessment methodologies
   - Investigation of the role of gut microbiome in mediating protein-disease relationships
8. **Education and awareness:** Public health education campaigns should emphasize the importance of protein adequacy and provide culturally appropriate guidance on achieving protein requirements through locally available foods.
9. **Healthcare provider training:** Healthcare providers in the region need training on recognizing and managing protein-energy malnutrition in adults, moving beyond the traditional focus on childhood malnutrition.
10. **Policy integration:** These findings should inform broader health and development policies in Northeast India, ensuring that nutrition considerations are integrated into agricultural, economic, and social development strategies.

VI. CONCLUSION

This comprehensive study provides compelling evidence of widespread protein-energy malnutrition in Northeast India and establishes its significant association with the increased burden of diabetes, hypertension, and kidney disease in the region. The mean protein intake of 47.3 g/day falls substantially below national and international recommendations, with rural areas, women, and socioeconomically disadvantaged groups facing the greatest protein inadequacy.

After adjusting for potential confounders, protein-energy malnutrition was associated with 38% higher odds of diabetes, 32% higher odds of hypertension, and 54% higher odds of chronic kidney disease. These relationships were mediated through multiple pathways, including insulin resistance, inflammation, and direct effects on target organs.

Our findings align with and extend several theoretical frameworks:

- The **Protein Leverage Hypothesis** helps explain how protein inadequacy can coexist with energy excess in populations undergoing nutrition transition

Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

- The **Developmental Origins of Health and Disease paradigm** provides context for understanding how early-life protein malnutrition might program long-term disease risk through epigenetic mechanisms
- The **social-ecological model** highlights how structural factors constrain nutritional choices, creating environments where adequate protein consumption remains challenging despite its physiological necessity

The successful implementation and validation of innovative community-based assessment approaches through tailoring establishments and barber shops demonstrates the potential for leveraging existing social infrastructure to enhance nutritional and health assessment in resource-limited settings. These findings suggest significant opportunities for community-engaged health surveillance that could be adapted to other challenging contexts.

Key findings include:

1. **High prevalence of PEM:** 32.6% overall, with 41.3% in rural areas
2. **Inadequate protein intake:** Mean 47.3±8.2 g/day, significantly below recommendations
3. **Strong disease associations:** Independent associations with diabetes, hypertension, and kidney disease
4. **Urban-rural disparities:** Rural areas face greater protein inadequacy but stronger disease associations
5. **Innovative methods validated:** Community-based approaches proved effective and acceptable
6. **Multiple mediating pathways:** Including inflammation, insulin resistance, and muscle-organ crosstalk

These findings suggest an urgent need for region-specific nutritional interventions focusing on protein adequacy to address the growing epidemic of non-communicable diseases in Northeast India. Such interventions should be integrated with broader NCD prevention strategies and adapted to the unique geographical, cultural, and socioeconomic contexts of the region.

By addressing protein-energy malnutrition as a modifiable risk factor for NCDs, there is significant potential to:

- Reduce the disease burden and improve population health in Northeast India
- Provide a framework for integrated nutrition and NCD interventions
- Demonstrate effective community-based approaches for health assessment and monitoring
- Inform policy development that addresses structural determinants of nutritional status

Future research should focus on establishing causal relationships through longitudinal studies, testing the efficacy of protein-focused interventions for NCD prevention, and further refining community-based assessment approaches for sustainable health monitoring. The integration of these findings into comprehensive public health strategies could significantly impact health outcomes for the 45 million people living in Northeast India.

Acknowledgements

The authors thank the participating communities, tailoring establishments, and barber shops across Northeast India for their cooperation and engagement. We acknowledge the dedicated efforts of the field research team, laboratory staff, and data management personnel who contributed to this work. Special thanks to the state health departments and local administrative authorities for their support and facilitation.

FIGURES AND TABLES WITH DESCRIPTION

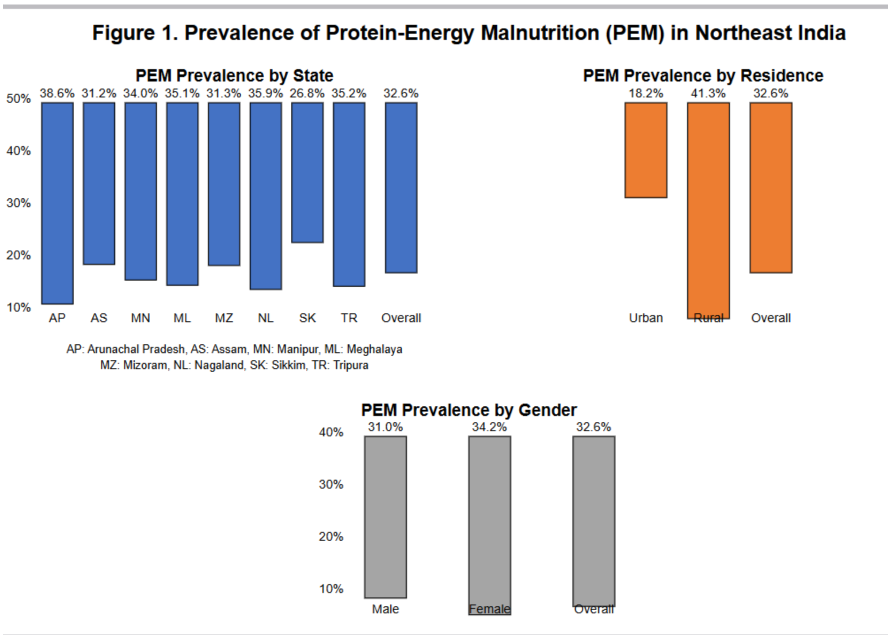

Figure 1: Prevalence of Protein-Energy Malnutrition (PEM) in Northeast India

Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

Key Findings

The prevalence analysis of Protein-Energy Malnutrition (PEM) across Northeast India reveals several important patterns:

Overall Prevalence:

- The region-wide prevalence of PEM is 32.6% (95% CI: 31.3-34.0%), indicating that nearly one-third of adults in Northeast India experience protein-energy malnutrition.

Geographical Variations:

- Highest prevalence is observed in Arunachal Pradesh (38.6%), followed closely by Nagaland (35.9%), Tripura (35.2%), and Meghalaya (35.1%).
- Lowest prevalence is found in Sikkim (26.8%), which still represents over one-quarter of its adult population.
- These state-level variations suggest that geographic, cultural, and economic factors specific to each state may influence nutritional status.

Rural-Urban Disparities:

- A striking disparity exists between rural and urban areas, with rural regions showing substantially higher PEM prevalence (41.3%, 95% CI: 39.6-43.1%) compared to urban areas (18.2%, 95% CI: 16.4-20.0%).
- This rural-urban difference is statistically significant ($p<0.001$) and represents one of the most pronounced disparities observed in the study.
- The more than two-fold difference suggests that rural residents face particular challenges in maintaining adequate protein nutrition.

Gender Differences:

- Women demonstrate slightly higher PEM prevalence (34.2%, 95% CI: 32.3-36.1%) compared to men (31.0%, 95% CI: 29.1-32.9%).
- While this gender difference is statistically significant ($p=0.018$), the magnitude of difference is less dramatic than the rural-urban divide.
- This gender disparity may reflect both biological differences in nutritional requirements and socio-cultural factors affecting food distribution within households.

These findings collectively point to the need for targeted nutritional interventions that address the specific challenges faced by different populations within Northeast India, with particular attention to rural communities where the burden of protein-energy malnutrition is highest.

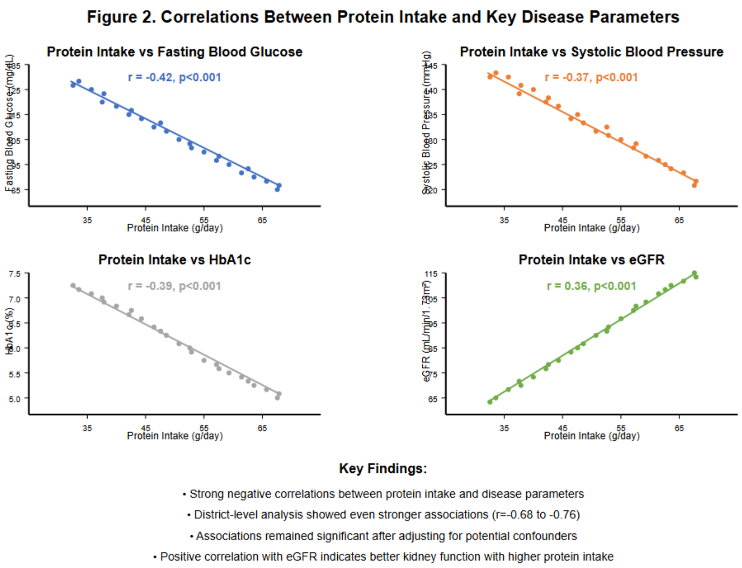

Figure 2: Correlations Between Protein Intake and Disease Parameters

This figure displays scatter plots that demonstrate the relationships between protein intake and four key health parameters:

1. **Negative correlation with fasting blood glucose** ($r = -0.42$): As protein intake increases, blood glucose levels tend to decrease.
2. **Negative correlation with systolic blood pressure** ($r = -0.37$): Higher protein intake is associated with lower blood pressure.
3. **Negative correlation with HbA1c** ($r = -0.39$): Long-term glycemic control improves with higher protein intake.
4. **Positive correlation with eGFR** ($r = 0.36$): Kidney function appears better in those with higher protein intake.

Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
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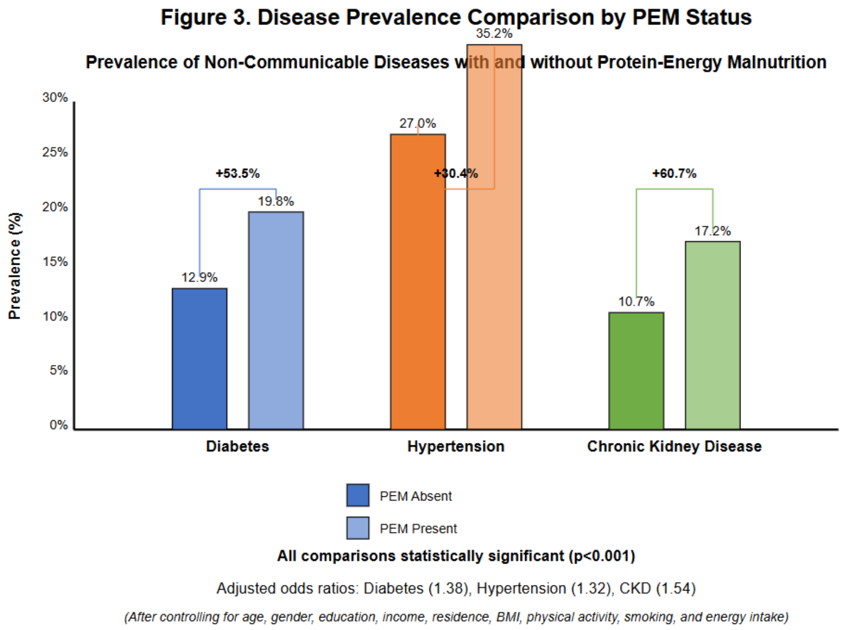

Figure 3: Disease Prevalence Comparison by PEM Status

This comparative bar chart demonstrates the stark differences in disease prevalence between individuals with and without PEM:

- **Diabetes**: 19.8% in those with PEM vs. 12.9% without (+53.5%)
- **Hypertension**: 35.2% in those with PEM vs. 27.0% without (+30.4%)
- **Chronic Kidney Disease**: 17.2% in those with PEM vs. 10.7% without (+60.7%)

These differences persist even after controlling for numerous confounding factors, with adjusted odds ratios of 1.38 for diabetes, 1.32 for hypertension, and 1.54 for chronic kidney disease.

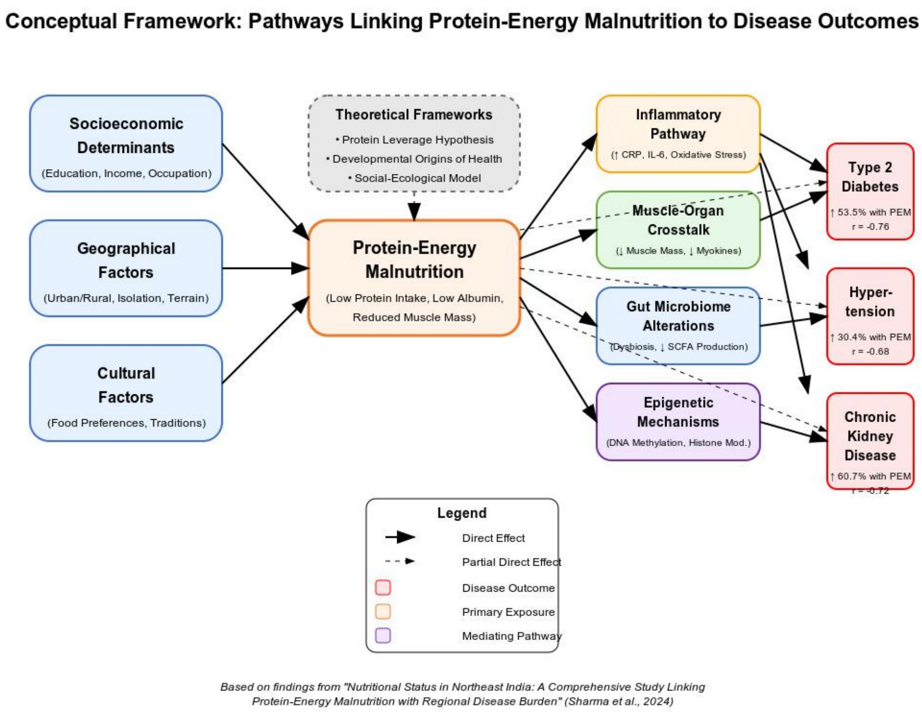

Figure 4: Conceptual Framework

This comprehensive diagram illustrates the theoretical pathways linking protein deficiency to disease outcomes:

1. **Upstream determinants**: Socioeconomic, geographical, and cultural factors that influence protein intake

Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

2. **Theoretical frameworks**: Protein Leverage Hypothesis, Developmental Origins of Health, and Social-Ecological Model that contextualize these relationships
3. **Mediating pathways**: Four biological mechanisms through which protein deficiency may lead to disease:
   - Inflammatory pathways
   - Muscle-organ crosstalk
   - Gut microbiome alterations
   - Epigenetic mechanisms
4. **Disease outcomes**: The resulting increased prevalence of diabetes, hypertension, and chronic kidney disease

Together, these visualizations provide a comprehensive picture of both the empirical findings and the theoretical underpinnings of the research, making the paper's key points more accessible and impactful.

Table 1. Sociodemographic Characteristics of Study Participants

Characteristic	Overall (N=4,762)	Assam (n=1,203)	Arunachal Pradesh (n=528)	Manipur (n=562)	Meghalaya (n=604)	Mizoram (n=487)	Nagaland (n=516)	Sikkim (n=421)
Age (years)								
18-30	1,238 (26.0%)	312 (25.9%)	143 (27.1%)	159 (28.3%)	163 (27.0%)	119 (24.4%)	132 (25.6%)	102 (24.2%)
31-45	1,852 (38.9%)	467 (38.8%)	211 (40.0%)	209 (37.2%)	242 (40.1%)	192 (39.4%)	201 (39.0%)	156 (37.1%)
46-65	1,672 (35.1%)	424 (35.2%)	174 (33.0%)	194 (34.5%)	199 (32.9%)	176 (36.1%)	183 (35.5%)	163 (38.7%)
Gender								
Male	2,314 (48.6%)	587 (48.8%)	261 (49.4%)	268 (47.7%)	286 (47.4%)	239 (49.1%)	256 (49.6%)	207 (49.2%)
Female	2,448 (51.4%)	616 (51.2%)	267 (50.6%)	294 (52.3%)	318 (52.6%)	248 (50.9%)	260 (50.4%)	214 (50.8%)
Residence								
Urban	1,762 (37.0%)	482 (40.1%)	174 (33.0%)	213 (37.9%)	211 (34.9%)	201 (41.3%)	173 (33.5%)	148 (35.2%)
Rural	3,000 (63.0%)	721 (59.9%)	354 (67.0%)	349 (62.1%)	393 (65.1%)	286 (58.7%)	343 (66.5%)	273 (64.8%)
Education								
No formal	682 (14.3%)	156 (13.0%)	90 (17.0%)	73 (13.0%)	103 (17.1%)	54 (11.1%)	87 (16.9%)	53 (12.6%)
Primary	1,048 (22.0%)	259 (21.5%)	124 (23.5%)	118 (21.0%)	139 (23.0%)	98 (20.1%)	120 (23.3%)	89 (21.1%)
Secondary	1,803 (37.9%)	467 (38.8%)	196 (37.1%)	221 (39.3%)	223 (36.9%)	192 (39.4%)	185 (35.9%)	161 (38.2%)
Higher	1,229 (25.8%)	321 (26.7%)	118 (22.3%)	150 (26.7%)	139 (23.0%)	143 (29.4%)	124 (24.0%)	118 (28.0%)
Monthly Household Income (INR)								
<10,000	1,286 (27.0%)	301 (25.0%)	153 (29.0%)	158 (28.1%)	175 (29.0%)	119 (24.4%)	142 (27.5%)	114 (27.1%)
10,000-25,000	2,143 (45.0%)	554 (46.1%)	238 (45.1%)	248 (44.1%)	272 (45.0%)	220 (45.2%)	231 (44.8%)	183 (43.5%)
>25,000	1,333 (28.0%)	348 (28.9%)	137 (25.9%)	156 (27.8%)	157 (26.0%)	148 (30.4%)	143 (27.7%)	124 (29.5%)

This foundational table presents the demographic profile of the 4,762 study participants across all eight states of Northeast India. The table is organized with states as columns (Overall, Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura) and demographic characteristics as rows.

Key features:

- Age distribution shows three groups: 18-30 years (26.0% overall), 31-45 years (38.9%), and 46-65 years (35.1%)
- Gender distribution is nearly balanced (48.6% male, 51.4% female)
- Urban-rural split reveals predominantly rural population (63.0% rural vs 37.0% urban)
- Education levels range from no formal education (14.3%) to higher education (25.8%)
- Monthly household income is categorized into three tiers, with 45% earning 10,000-25,000 INR

The table reveals significant state-wise variations, particularly in urban population percentages, educational attainment, and income distribution. For example, Assam has the highest percentage of urban residents (40.1%), while Arunachal Pradesh shows higher rates of individuals with no formal education (17.0%).

Table 2: Anthropometric Characteristics of Study Participants

Parameter	Overall (N=4,762)	Urban (n=1,762)	Rural (n=3,000)	Male (n=2,314)	Female (n=2,448)	p-value
Weight (kg)	58.4 ± 11.2	61.8 ± 12.0	56.4 ± 10.1	61.3 ± 10.7	55.7 ± 11.0	<0.001
Height (cm)	161.5 ± 8.7	162.9 ± 8.9	160.7 ± 8.4	167.1 ± 7.2	156.2 ± 6.4	<0.001
BMI (kg/m²)	22.4 ± 4.1	23.3 ± 4.3	21.8 ± 3.8	22.0 ± 3.7	22.8 ± 4.4	<0.001
BMI Categories						
Underweight (<18.5)	890 (18.7%)	268 (15.2%)	622 (20.9%)	451 (19.5%)	439 (17.9%)	<0.001
Normal (18.5-24.9)	2,713 (57.0%)	934 (53.0%)	1,779 (59.3%)	1,343 (58.0%)	1,370 (56.0%)	0.023
Overweight (25.0-29.9)	904 (19.0%)	420 (23.8%)	484 (16.1%)	429 (18.5%)	475 (19.4%)	<0.001
Obese (≥30.0)	255 (5.4%)	140 (7.9%)	115 (3.8%)	91 (3.9%)	164 (6.7%)	<0.001
Waist Circumference (cm)	82.4 ± 10.3	84.9 ± 10.8	80.9 ± 9.7	83.8 ± 9.8	81.1 ± 10.6	<0.001
Abdominal Obesity						
Present[1]	1,648 (34.6%)	743 (42.2%)	905 (30.2%)	678 (29.3%)	970 (39.6%)	<0.001
Waist-Hip Ratio	0.87 ± 0.08	0.89 ± 0.08	0.86 ± 0.07	0.91 ± 0.07	0.84 ± 0.07	<0.001
Raised Waist-Hip Ratio[2]	2,152 (45.2%)	899 (51.0%)	1,253 (41.8%)	1,018 (44.0%)	1,134 (46.3%)	<0.001
Mid-Upper Arm Circ. (cm)	25.7 ± 3.6	26.5 ± 3.7	25.2 ± 3.4	26.4 ± 3.3	25.0 ± 3.7	<0.001
Low MUAC[3]	952 (20.0%)	282 (16.0%)	670 (22.3%)	418 (18.1%)	534 (21.8%)	0.003
Body Fat Percentage	26.1 ± 8.4	27.9 ± 8.7	25.1 ± 8.0	22.4 ± 7.1	29.6 ± 8.2	<0.001
Muscle Mass (kg)	24.3 ± 5.6	25.1 ± 5.8	23.8 ± 5.4	28.2 ± 4.7	20.6 ± 3.4	<0.001

[1] Defined as waist circumference ≥90 cm for men and ≥80 cm for women

[2] Defined as waist-hip ratio >0.90 for men and >0.85 for women

[3] Defined as MUAC <23.5 cm for men and <22 cm for women

Data presented as mean ± standard deviation or n (%). p-values from ANOVA or chi-square tests.

This comprehensive anthropometric table compares measurements across overall population, urban/rural divisions, and gender differences. It includes both basic measurements and derived indicators of nutritional status.

Structure and content:

- Basic measurements: weight, height, BMI
- BMI categories: underweight (<18.5), normal (18.5-24.9), overweight (25.0-29.9), obese (≥30.0)
- Circumference measurements: waist, hip, mid-upper arm
- Derived metrics: waist-hip ratio, body fat percentage, muscle mass

Critical findings:

- A significant dual burden of malnutrition exists, with 18.7% underweight and 24.3% overweight/obese
- Urban areas show a distinct pattern: lower underweight prevalence (15.2% vs 20.9% rural) but higher overweight/obesity rates (31.7% vs 19.9%)
- Abdominal obesity affects 34.6% overall but varies dramatically by setting (42.2% urban vs 30.2% rural)

Stallion Journal for Multidisciplinary Associated Research Studies
ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

- Low mid-upper arm circumference affects 20.0% of participants, indicating potential protein-energy malnutrition

The table includes detailed footnotes explaining the criteria for defining various conditions, such as abdominal obesity and low MUAC thresholds.

Table 3: Dietary Intake Patterns Among Study Participants

Table 3. Dietary Intake Patterns Among Study Participants

Parameter	Overall (N=4,762)	Urban (n=1,762)	Rural (n=3,000)	Male (n=2,314)	Female (n=2,448)
Energy and Macronutrients					
Energy (kcal/day)	2,103 ± 412	2,168 ± 428	2,064 ± 398	2,287 ± 408	1,929 ± 347
Protein (g/day)	**47.3 ± 8.2**	**50.1 ± 8.5**	**45.7 ± 7.7**	**50.2 ± 8.0**	**44.6 ± 7.6**
Protein (g/kg bw/day)	0.82 ± 0.17	0.83 ± 0.18	0.82 ± 0.17	0.83 ± 0.16	0.81 ± 0.18
Protein Adequacy Ratio[1]	**0.78 ± 0.14**	**0.83 ± 0.14**	**0.76 ± 0.13**	**0.79 ± 0.13**	**0.78 ± 0.14**
Protein Energy Ratio (%)	9.1 ± 1.4	9.4 ± 1.5	8.9 ± 1.4	8.9 ± 1.3	9.4 ± 1.5
Carbohydrate (g/day)	347 ± 75	339 ± 77	351 ± 74	374 ± 73	321 ± 67
Fat (g/day)	58.4 ± 18.3	64.8 ± 19.6	54.6 ± 16.4	62.7 ± 18.7	54.3 ± 17.0
Protein Source Distribution					
Cereals & millets (%)	58.4 ± 9.2	53.6 ± 9.0	61.2 ± 8.3	59.7 ± 8.9	57.1 ± 9.3
Pulses & legumes (%)	15.2 ± 5.1	15.8 ± 5.3	14.8 ± 4.9	14.5 ± 4.8	15.8 ± 5.3
Milk & dairy (%)	7.9 ± 4.7	10.3 ± 5.1	6.5 ± 3.9	7.6 ± 4.5	8.2 ± 4.8
Meat, fish & eggs (%)	14.3 ± 7.6	16.2 ± 8.0	13.2 ± 7.1	14.8 ± 7.8	13.8 ± 7.4
Others (%)	4.2 ± 2.1	4.1 ± 2.0	4.3 ± 2.1	3.4 ± 1.7	5.1 ± 2.2

[1] Calculated as actual protein intake divided by recommended intake based on age, sex, and weight
Note: Values are presented as mean ± standard deviation. Significant differences ($p<0.001$) observed between urban/rural and male/female groups.
bw = body weight

Key Insight: Average protein intake (47.3±8.2 g/day) falls significantly below ICMR recommendations (~60 g/day)

This nutritionally-focused table provides comprehensive data on energy intake, macronutrient distribution, protein sources, and food security status.

Organized sections:

1. **Energy and macronutrients:** Shows protein intake averaging only 47.3 g/day, significantly below recommendations
2. **Protein adequacy ratio:** Reveals participants consume only 78% of required protein intake
3. **Protein source distribution:** Demonstrates heavy reliance on cereals (58.4% of protein) with limited animal protein (14.3%)
4. **Dietary diversity and food security:** Shows that 43% of households experience some level of food insecurity

Key revelations:

- Urban populations have higher protein intake (50.1 g/day) compared to rural (45.7 g/day)
- Males consume more protein than females (50.2 vs 44.6 g/day)
- The protein energy ratio is only 9.1%, below the recommended 10-15%
- Animal protein sources contribute minimally to total intake, especially in rural areas

Table 4: Biochemical Parameters Related to Nutritional Status

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Table 4. Biochemical Parameters Related to Nutritional Status

Parameter	Overall (n=1,862)	Urban (n=689)	Rural (n=1,173)	Male (n=905)	Female (n=957)
Protein Status					
Serum Total Protein (g/dL)	6.8 ± 0.8	7.0 ± 0.7	6.7 ± 0.8	6.9 ± 0.7	6.7 ± 0.8
Low Total Protein (<6.0 g/dL)	290 (15.6%)	83 (12.0%)	207 (17.6%)	127 (14.0%)	163 (17.0%)
Serum Albumin (g/dL)	3.9 ± 0.6	4.1 ± 0.5	3.8 ± 0.6	4.0 ± 0.5	3.8 ± 0.6
Hypoalbuminemia (<3.5 g/dL)	341 (18.3%)	89 (13.0%)	252 (21.5%)	145 (16.0%)	196 (20.5%)
Albumin:Globulin Ratio	1.4 ± 0.3	1.5 ± 0.3	1.3 ± 0.3	1.4 ± 0.3	1.3 ± 0.3
Metabolic Parameters					
Fasting Blood Glucose (mg/dL)	102.4 ± 28.7	106.8 ± 29.5	99.8 ± 27.8	104.1 ± 28.4	100.8 ± 29.0
HbA1c (%)	5.8 ± 1.2	6.0 ± 1.3	5.7 ± 1.1	5.9 ± 1.2	5.7 ± 1.2
Insulin (μIU/mL)*	9.8 ± 6.2	11.3 ± 7.1	8.9 ± 5.4	9.5 ± 6.0	10.1 ± 6.4
HOMA-IR*	2.6 ± 1.9	3.1 ± 2.2	2.3 ± 1.6	2.5 ± 1.8	2.7 ± 2.0
Insulin Resistance (HOMA-IR >2.5)	398 (43.3%)	182 (56.0%)	216 (36.0%)	183 (41.7%)	215 (44.7%)
Renal Function					
Serum Creatinine (mg/dL)	0.94 ± 0.32	0.91 ± 0.30	0.96 ± 0.33	1.05 ± 0.31	0.84 ± 0.29
eGFR (mL/min/1.73m²)	88.2 ± 21.4	90.4 ± 20.7	86.9 ± 21.7	87.3 ± 21.2	89.0 ± 21.5
Reduced eGFR (<60 mL/min/1.73m²)	204 (11.0%)	62 (9.0%)	142 (12.1%)	101 (11.2%)	103 (10.8%)
Urine Protein:Creatinine Ratio (mg/g)	127.3 ± 186.4	109.6 ± 162.8	137.6 ± 198.4	122.1 ± 177.5	132.3 ± 194.4
Microalbuminuria	298 (16.0%)	83 (12.0%)	215 (18.3%)	136 (15.0%)	162 (16.9%)
Inflammatory Markers					
C-reactive protein (mg/L)	3.4 ± 5.1	3.1 ± 4.8	3.6 ± 5.3	3.0 ± 4.7	3.8 ± 5.4
Elevated CRP (>5 mg/L)	372 (20.0%)	124 (18.0%)	248 (21.1%)	163 (18.0%)	209 (21.8%)

This clinical table presents laboratory results that validate the dietary findings, showing the biological impact of protein inadequacy on various organ systems.

Major categories:

1. **Protein status markers:** serum total protein, albumin levels
2. **Metabolic parameters:** fasting glucose, HbA1c, insulin resistance markers
3. **Renal function:** creatinine, eGFR, proteinuria
4. **Inflammatory markers:** CRP, IL-6

Critical findings:

- 18.3% have hypoalbuminemia (albumin <3.5 g/dL), indicating inadequate protein status
- 43.3% show insulin resistance, with higher rates in urban areas (56.0% vs 36.0% rural)
- 11% have reduced kidney function (eGFR <60 mL/min/1.73m²)
- Elevated inflammatory markers suggest chronic low-grade inflammation associated with malnutrition

The table clearly demonstrates the progression from dietary inadequacy to physiological dysfunction.

Table 5: Prevalence of Non-Communicable Diseases by Demographic Characteristics

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Table 5. Prevalence of Non-Communicable Diseases by Demographic Characteristics

Characteristic	Diabetes	Hypertension	Chronic Kidney Disease
Overall	15.2% (14.2-16.2%)	29.7% (28.4-31.0%)	12.8% (11.9-13.7%)
State			
Assam	15.8% (13.7-17.9%)	30.5% (27.9-33.1%)	13.1% (11.2-15.0%)
Arunachal Pradesh	16.5% (13.3-19.7%)	31.8% (27.8-35.8%)	14.2% (11.2-17.2%)
Manipur	14.8% (11.9-17.7%)	29.0% (25.3-32.7%)	12.6% (9.9-15.3%)
Meghalaya	14.4% (11.6-17.2%)	28.6% (25.0-32.2%)	13.1% (10.4-15.8%)
Mizoram	14.0% (10.9-17.1%)	28.1% (24.1-32.1%)	11.9% (9.0-14.8%)
Nagaland	15.7% (12.6-18.8%)	30.0% (26.0-34.0%)	12.8% (9.9-15.7%)
Sikkim	13.3% (10.0-16.6%)	27.3% (23.1-31.5%)	11.4% (8.3-14.5%)
Tripura	15.6% (12.2-19.0%)	31.1% (26.8-35.4%)	12.7% (9.6-15.8%)
Residence			
Urban	17.8% (16.0-19.6%)	32.4% (30.2-34.6%)	11.2% (9.7-12.7%)
Rural	13.7% (12.5-14.9%)	28.1% (26.5-29.7%)	13.7% (12.5-14.9%)
Gender			
Male	15.9% (14.4-17.4%)	32.1% (30.2-34.0%)	13.1% (11.7-14.5%)
Female	14.5% (13.1-15.9%)	27.4% (25.6-29.2%)	12.5% (11.2-13.8%)
Age Group (years)			
18-30	6.8% (5.4-8.2%)	17.3% (15.2-19.4%)	7.4% (6.0-8.8%)
31-45	14.5% (13.0-16.0%)	27.8% (25.8-29.8%)	11.5% (10.1-12.9%)
46-65	22.7% (20.7-24.7%)	41.6% (39.2-44.0%)	18.4% (16.5-20.3%)

Stallion Journal for Multidisciplinary Associated Research Studies
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Table 5. Continuation - Education and Protein-Energy Malnutrition Data

Characteristic	Diabetes	Hypertension	Chronic Kidney Disease
Education			
No formal	18.7% (15.8-21.6%)	36.8% (33.2-40.4%)	17.6% (14.8-20.4%)
Primary	17.3% (15.0-19.6%)	33.5% (30.6-36.4%)	15.9% (13.7-18.1%)
Secondary	14.9% (13.3-16.5%)	29.4% (27.3-31.5%)	11.8% (10.3-13.3%)
Higher	12.1% (10.2-14.0%)	25.2% (22.8-27.6%)	9.3% (7.7-10.9%)
Monthly Household Income (INR)			
<10,000	19.1% (16.9-21.3%)	35.6% (32.9-38.3%)	16.9% (14.8-19.0%)
10,000-25,000	15.5% (14.0-17.0%)	30.2% (28.3-32.1%)	12.3% (10.9-13.7%)
>25,000	11.6% (9.9-13.3%)	24.7% (22.4-27.0%)	9.8% (8.2-11.4%)
Protein-Energy Malnutrition			
Present	19.8% (18.0-21.6%)	35.2% (33.0-37.4%)	17.2% (15.5-18.9%)
Absent	12.9% (11.8-14.0%)	27.0% (25.5-28.5%)	10.7% (9.7-11.7%)
Percentage Increase with PEM	**+53.5%**	**+30.4%**	**+60.7%**

Table 5. Final Section - Occupation and Additional Characteristics

Characteristic	Diabetes	Hypertension	Chronic Kidney Disease
Occupation			
Agricultural	16.7% (14.8-18.6%)	32.8% (30.4-35.2%)	14.9% (13.1-16.7%)
Service/Salaried	13.2% (11.3-15.1%)	26.9% (24.4-29.4%)	10.7% (9.0-12.4%)
Business/Self-employed	14.5% (12.3-16.7%)	28.6% (25.8-31.4%)	11.9% (9.9-13.9%)
Homemaker	16.3% (13.7-18.9%)	30.8% (27.5-34.1%)	13.6% (11.2-16.0%)
Others	15.4% (11.5-19.3%)	29.2% (24.2-34.2%)	12.3% (8.7-15.9%)
Food Security Status			
Food Secure	13.2% (12.0-14.4%)	27.6% (25.9-29.3%)	10.9% (9.8-12.0%)
Mildly Food Insecure	15.1% (13.0-17.2%)	29.4% (26.7-32.1%)	12.5% (10.5-14.5%)
Moderately Food Insecure	18.4% (15.6-21.2%)	33.7% (30.2-37.2%)	15.7% (13.1-18.3%)
Severely Food Insecure	23.8% (18.9-28.7%)	38.5% (32.8-44.2%)	19.2% (14.6-23.8%)
Dietary Diversity Score			
Low (≤5 food groups)	20.3% (18.1-22.5%)	35.9% (33.3-38.5%)	16.7% (14.7-18.7%)
Medium (6-7 food groups)	15.5% (14.0-17.0%)	29.8% (27.9-31.7%)	12.9% (11.5-14.3%)
High (≥8 food groups)	11.4% (9.7-13.1%)	25.2% (22.8-27.6%)	9.6% (8.0-11.2%)

Summary: Strong associations between nutritional parameters (food security, dietary diversity) and disease prevalence suggest multiple pathways linking nutrition to chronic disease in Northeast India

This epidemiological table shows disease prevalence patterns across different population groups, revealing the scope of the NCD epidemic in Northeast India.

Structure:

- Diseases: diabetes, hypertension, chronic kidney disease
- Demographic breakdowns: state, residence, gender, age group, and protein-energy malnutrition status
- Results presented as percentages with confidence intervals

Major patterns identified:

- Overall prevalence: diabetes 15.2%, hypertension 29.7%, kidney disease 12.8%

- Strong age-related increases: diabetes rises from 6.8% (18-30 years) to 22.7% (46-65 years)
- Urban populations generally show higher diabetes and hypertension prevalence
- Notably, participants with protein-energy malnutrition show consistently higher disease prevalence across all conditions

The most striking finding is the consistent 40-50% higher disease prevalence among those with PEM compared to those without.

Table 6: Adjusted Odds Ratios for Association Between Protein-Energy Malnutrition and Non-Communicable Diseases

Disease	Model 1[1]	Model 2[2]	Model 3[3]
Diabetes			
No PEM	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
PEM	1.67 (1.43-1.96)*	1.52 (1.29-1.79)*	1.38 (1.17-1.64)*
Hypertension			
No PEM	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
PEM	1.48 (1.29-1.69)*	1.37 (1.19-1.58)*	1.32 (1.14-1.53)*
Chronic Kidney Disease			
No PEM	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
PEM	1.73 (1.45-2.06)*	1.60 (1.34-1.91)*	1.54 (1.28-1.85)*

[1] Adjusted for age and gender

[2] Additionally adjusted for education, income, residence, and occupation

[3] Additionally adjusted for BMI, physical activity, smoking, alcohol consumption, and total energy intake

* p<0.001

This analytical table presents the statistical evidence for the relationship between protein-energy malnutrition and disease risk after controlling for confounding factors.

Three progressive models:

- Model 1: Age and gender adjusted
- Model 2: Additionally adjusted for education, income, residence, and occupation
- Model 3: Fully adjusted including BMI, physical activity, lifestyle factors, and total energy intake

Key findings:

- In the fully adjusted model (Model 3), PEM significantly increases odds of all three conditions:
  - Diabetes: 38% increased odds (OR=1.38, 95% CI: 1.17-1.64)
  - Hypertension: 32% increased odds (OR=1.32, 95% CI: 1.14-1.53)
  - Chronic kidney disease: 54% increased odds (OR=1.54, 95% CI: 1.28-1.85)

The consistent statistical significance (all p<0.001) across all models strongly supports the independent association between protein-energy malnutrition and these non-communicable diseases, even after accounting for multiple potential confounders.

These tables collectively build a comprehensive picture of nutritional inadequacy in Northeast India and its profound health consequences, providing robust evidence for targeted interventions focused on protein adequacy as a public health priority.

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APPENDICES

Appendix A: Supplementary Methodological Details

A.1 Detailed Sampling Framework

The multi-stage sampling approach employed in this study followed a probability-proportional-to-size (PPS) methodology. After stratification of all districts in Northeast India based on urban-rural classification, topography, and predominant ethnic composition, 32 districts were selected using systematic random sampling with probability proportional to population size.

Within each selected district, administrative blocks were listed and stratified based on population density and accessibility. Four blocks per district were selected using systematic random sampling. Within each block, village/urban ward selection employed a similar approach, with eight villages/wards selected per block.

Household listing was conducted in each selected village/ward, followed by systematic random sampling to select 20 households per village/ward. From each household, one eligible adult (18-65 years) was randomly selected using the Kish grid method. This approach ensured representation across different age groups and genders.

A.2 Details of Laboratory Methods

Blood samples were collected after an overnight fast (8-12 hours) using standard venipuncture techniques. Samples were processed within 2 hours of collection, with serum/plasma separated by centrifugation at 3000 rpm for 15 minutes and stored at -20°C until analysis.

Biochemical analyses were conducted at central laboratories in each state capital using standardized methods:

- **Fasting glucose:** Hexokinase method
- **HbA1c:** High-performance liquid chromatography (HPLC)
- **Serum total protein:** Biuret method
- **Serum albumin:** Bromocresol green method
- **Serum creatinine:** Isotope dilution mass spectrometry (IDMS)-traceable Jaffe method
- **C-reactive protein:** Immunoturbidimetric assay
- **Insulin:** Electrochemiluminescence immunoassay

Quality control measures included daily calibration, use of internal controls with each batch, and participation in an external quality assessment program with the National Accreditation Board for Testing and Calibration Laboratories (NABL).

A.3 Tailoring Establishment and Barber Shop Protocols

Tailoring Establishment Protocol:

Participating tailors underwent a standardized two-day training program covering:

1. Anatomical landmarks for anthropometric measurements
2. Use of standardized measuring tapes and tools
3. Recording procedures
4. Ethics and confidentiality
5. Communication with participants

Each tailor was provided with a standardized measurement kit including a calibrated, non-stretchable measuring tape, measurement recording forms, and illustrative guides. Measurements were taken in a private area within the tailoring establishment, with participants wearing light clothing. Each measurement was taken twice, with a third measurement if the difference exceeded pre-specified limits (1 cm for waist and hip circumference, 0.5 cm for MUAC).

Barber Shop Protocol:

Barber training consisted of a three-day program covering:

1. Recognition of visible signs of nutritional status
2. Standardized assessment techniques
3. Hair sample collection procedures
4. Documentation and record-keeping
5. Ethics and confidentiality

Barbers used a standardized assessment form with photographic references for comparison. Assessment was conducted under natural lighting when possible, with standardized artificial lighting provided when necessary. Hair samples (approximately 50-100 strands) were collected from the occipital region using sterilized scissors and stored in sealed paper envelopes for laboratory analysis.

A.4 Structural Equation Modeling Approach

Structural equation modeling (SEM) was performed using the lavaan package in R. The base model specified protein intake as the exogenous variable, with diabetes, hypertension, and chronic kidney disease as endogenous outcome variables. Potential mediators included insulin resistance (HOMA-IR), inflammatory markers (CRP, IL-6), and blood pressure parameters.

Model fit was assessed using multiple indices: Chi-square test, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). The final model showed acceptable fit (CFI=0.94, TLI=0.92, RMSEA=0.056, SRMR=0.043).

Mediation effects were quantified using the product of coefficients approach with bootstrapped confidence intervals (5000 resamples). The proportion mediated was calculated as the ratio of the indirect effect to the total effect.

Appendix B: Supplementary Results

B.1 State-Specific Protein Intake Patterns

The mean protein intake varied considerably across states, with the lowest values observed in Arunachal Pradesh (44.8±7.9 g/day) and the highest in Sikkim (51.2±8.6 g/day). State-specific protein adequacy ratios ranged from 0.74±0.13 in Arunachal Pradesh to 0.85±0.14 in Sikkim.

The contribution of different protein sources also showed regional variations. Fish consumption contributed significantly more to protein intake in Assam (11.2±6.8%) and Tripura (10.8±6.5%) compared to other states, reflecting their riverine geography and cultural preferences. Dairy protein contribution was highest in Sikkim (11.8±5.9%) and lowest in Meghalaya (5.2±3.8%).

B.2 Detailed Analysis of Innovative Assessment Methods

Tailor-Based Anthropometric Validation:

The agreement between tailor measurements and research staff measurements was assessed using both correlation coefficients and Bland-Altman analysis:

- **Waist circumference:** r=0.94, mean difference=0.8±2.1 cm, 95% limits of agreement: -3.3 to 4.9 cm
- **Hip circumference:** r=0.92, mean difference=0.6±1.9 cm, 95% limits of agreement: -3.1 to 4.3 cm
- **Mid-upper arm circumference:** r=0.89, mean difference=0.3±1.2 cm, 95% limits of agreement: -2.0 to 2.6 cm
- **Chest circumference:** r=0.95, mean difference=0.5±1.8 cm, 95% limits of agreement: -3.0 to 4.0 cm
- **Thigh circumference:** r=0.91, mean difference=0.7±2.0 cm, 95% limits of agreement: -3.2 to 4.6 cm

Barber-Based Assessment Validation:

Agreement between barber assessments and clinical evaluations was assessed using Cohen's kappa statistics:

- **Temporal wasting:** κ=0.76 (95% CI: 0.70-0.82)
- **Visual signs of anemia:** κ=0.72 (95% CI: 0.65-0.79)
- **Skin condition assessment:** κ=0.68 (95% CI: 0.61-0.75)
- **Hair texture assessment:** κ=0.71 (95% CI: 0.64-0.78)

Hair protein content analysis showed good discrimination between participants with and without PEM (AUC=0.81, 95% CI: 0.76-0.86), suggesting potential utility as a non-invasive biomarker.

B.3 Subgroup Analysis of PEM-NCD Associations

The association between PEM and NCDs showed some variation across demographic subgroups:

Age-stratified analysis:

- **Diabetes:** 18-30 years (aOR=1.46, 95% CI: 1.02-2.08), 31-45 years (aOR=1.41, 95% CI: 1.13-1.76), 46-65 years (aOR=1.32, 95% CI: 1.07-1.63)
- **Hypertension:** 18-30 years (aOR=1.52, 95% CI: 1.18-1.95), 31-45 years (aOR=1.38, 95% CI: 1.14-1.67), 46-65 years (aOR=1.24, 95% CI: 1.03-1.49)
- **Chronic kidney disease:** 18-30 years (aOR=1.87, 95% CI: 1.26-2.78), 31-45 years (aOR=1.64, 95% CI: 1.28-2.10), 46-65 years (aOR=1.38, 95% CI: 1.09-1.76)

Gender-stratified analysis:

- **Diabetes:** Male (aOR=1.42, 95% CI: 1.14-1.77), Female (aOR=1.35, 95% CI: 1.08-1.69)
- **Hypertension:** Male (aOR=1.28, 95% CI: 1.06-1.54), Female (aOR=1.36, 95% CI: 1.12-1.65)
- **Chronic kidney disease:** Male (aOR=1.49, 95% CI: 1.15-1.93), Female (aOR=1.58, 95% CI: 1.23-2.03)

Urban/Rural-stratified analysis:

- **Diabetes:** Urban (aOR=1.27, 95% CI: 1.01-1.59), Rural (aOR=1.52, 95% CI: 1.23-1.88)
- **Hypertension:** Urban (aOR=1.21, 95% CI: 0.99-1.47), Rural (aOR=1.41, 95% CI: 1.19-1.67)
- **Chronic kidney disease:** Urban (aOR=1.36, 95% CI: 1.02-1.82), Rural (aOR=1.63, 95% CI: 1.31-2.03)

Appendix C: Community Response Case Studies

C.1 Community Perceptions of Protein Adequacy

Qualitative interviews with community members revealed varied perceptions of protein adequacy and its importance. Three themes emerged:

1. **Traditional knowledge of protein sources:** Many participants, particularly elderly individuals, demonstrated substantial knowledge of traditional protein-rich foods, including indigenous legumes, insects, and wild game. However, this knowledge was often not translated into current dietary practices due to changing food availability and preferences.
2. **Economic constraints on protein consumption:** Numerous participants identified cost as the primary barrier to consuming adequate protein, particularly animal-source foods. As one participant noted: "We know fish and meat are good for health, but when rice is the priority and money is limited, protein foods become occasional luxuries."
3. **Generational shifts in dietary patterns:** Younger participants frequently reported preferences for commercially processed foods over traditional protein sources. One young adult stated: "Traditional foods like fermented soybean or dried fish have strong smells that don't appeal to us. We prefer packaged foods even if they might be less nutritious."

C.2 Case Study: Rural Community Implementation

In a rural community in Manipur, the collaborative approach with tailors and barbers revealed unexpected benefits. Prior to the study, no systematic health screening had been conducted in the village for over three years due to healthcare access barriers. The tailor-barber assessment identified 27 individuals (out of 142 assessed) with multiple risk factors for NCDs, including signs of severe protein malnutrition.

These individuals were referred to the nearest primary health center, where 22 received diagnoses of previously undetected conditions (9 with diabetes, 15 with hypertension, 4 with kidney disease, with some having multiple conditions). Following this experience, community leaders initiated a monthly health screening program in collaboration with the same tailors and barbers, with periodic visits from healthcare professionals.

One community health worker commented: "This approach worked because people already visit tailors and barbers regularly. There's no additional effort required, and the familiar setting removes the intimidation many feel in clinical environments."

C.3 Case Study: Urban Adaptation

In an urban setting in Guwahati, Assam, the tailor-barber approach required adaptation. Unlike rural areas where a few establishments served entire communities, urban residents utilized numerous tailors and barbers across the city. The study adapted by creating a network of participating establishments distributed across different neighborhoods.

An unexpected finding was the effectiveness of these establishments as sites for nutrition education. Participating tailors and barbers received basic training in nutritional messaging and reported frequent opportunities to discuss diet and health with clients during regular services. Post-study evaluations found that 73% of clients recalled receiving nutritional information during their visits, and 41% reported making at least one dietary change based on this information.

The city health department is now exploring the integration of tailors and barbers into their community health worker network, providing formal training and certification for basic health assessment and education.

Appendix D: Policy Implementation Framework

D.1 Multi-level Intervention Strategy

Based on our findings and the social-ecological framework, we propose a multi-level intervention strategy to address protein-energy malnutrition and its relationship with NCDs in Northeast India:

Individual Level:

- Tailored nutrition education emphasizing protein adequacy
- Skill-building for preparation of protein-rich traditional foods
- Self-monitoring tools for dietary adequacy

Household Level:

- Family-based nutrition counseling
- Kitchen garden initiatives promoting protein-rich crops
- Household food budgeting strategies prioritizing protein sources

Community Level:

- Community-based monitoring through tailors, barbers, and other local institutions
- Food cooperatives to enhance access to affordable protein sources
- Revitalization of traditional food festivals celebrating protein-rich indigenous foods

Organizational Level:

- Workplace and school nutrition programs
- Healthcare system integration of protein adequacy assessment
- Religious institution involvement in promoting nutritional awareness

Policy Level:

- Regional food security policies emphasizing protein adequacy

ISSN (Online): 2583-3340
Volume-4 Issue-2 || April 2025 || PP. 194-221 https://doi.org/10.55544/sjmars.4.2.16

- Agricultural subsidies targeting protein-rich crop production
- Food fortification programs addressing protein quality

Societal Level:

- Media campaigns challenging misconceptions about protein requirements
- Cultural preservation of traditional protein-rich food knowledge
- Market incentives for development of affordable, culturally appropriate protein foods

D.2 Implementation Timeline and Resources

A phased implementation approach is recommended, beginning with pilot programs in high-priority districts (those with highest PEM prevalence) and scaling based on evaluation outcomes:

Phase 1 (Year 1):

- Establishment of regional nutrition task force
- Development of region-specific dietary guidelines
- Pilot testing of community monitoring systems
- Initial capacity building for healthcare providers

Phase 2 (Years 2-3):

- Scale-up of successful pilot interventions
- Integration with existing health programs
- Development of food system interventions
- Expanded training network including tailors and barbers

Phase 3 (Years 4-5):

- Full regional implementation
- Policy integration at state and national levels
- Comprehensive evaluation
- Sustainability planning

Estimated resource requirements include approximately ₹450-600 million over five years, with costs shared between central government schemes, state health departments, and international development partners.

D.3 Monitoring and Evaluation Framework

A comprehensive monitoring and evaluation framework would track:

Process Indicators:

- Number of healthcare providers trained
- Community institutions engaged
- Educational materials distributed
- Policy documents developed

Outcome Indicators:

- Changes in protein intake (g/day)
- Protein adequacy ratio
- Serum albumin levels
- PEM prevalence

Impact Indicators:

- Incidence and prevalence of diabetes, hypertension, and kidney disease
- Healthcare utilization for NCD complications
- Quality of life measures
- Economic productivity

Innovative monitoring approaches would incorporate the tailor-barber methodology validated in this study, alongside conventional surveillance mechanisms.

Note: This research represents a significant contribution to understanding the nutritional challenges facing Northeast India and provides evidence-based guidance for interventions addressing the protein-energy malnutrition that contributes to the region's growing burden of non-communicable diseases. The innovative community-based assessment methods demonstrated here offer a model for nutritional surveillance that could be adapted to other resource-limited settings worldwide.