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Enhancing ethnomathematical-ethnolinguistic understandings: A problem-based learning approach for postgraduate Sundanese language students

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ABSTRACT

As an interdisciplinary field within ethnolinguistics, ethnomathematics presents distinctive pedagogical challenges at the postgraduate level; however, research on Problem-Based Learning (PBL) in this context remains limited. This study examines postgraduate students' perceptions of PBL for learning ethnomathematics and meaning-making in an ethnolinguistics course, investigates how the students use SFL metafunctions, including transitivity choices within the ideational metafunction, in representing ethnomathematical knowledge, and proposes a mathematical model of knowledge growth during PBL. This study used mixed methods, combining a qualitative case study with descriptive statistics, to examine postgraduate students' experiences with PBL in an ethnolinguistics course focused on ethnomathematics. The qualitative approach captured the richness of students' perceptions, learning processes, and outcomes in an authentic classroom context. The quantitative approach focused on proposing a mathematical model using differential equations to represent how the PBL approach contributes to knowledge acquisition over time. The study used multiple data sources, questionnaires, observations, and documentary analysis, to achieve triangulation. Findings indicate that students perceived PBL as enhancing cognitive development (90%), reflective capacity (91%), and critical thinking (93%). Collaborative PBL also promoted communicative competence, motivation, and confidence in sharing cultural-mathematical knowledge. SFL analysis revealed the use of ideational metafunctions through material and relational processes to encode mathematical and astronomical concepts; interpersonal metafunctions through declarative mood and graded modality to construe knowledge as factual and authoritative; and textual metafunctions through thematic progression and lexical cohesion to organize knowledge systematically. Students successfully documented Sundanese numerical systems, traditional measurement units such as *kibik* and *bata*, and calendrical calculations in the *Palintangan* manuscript. Building on these learning dynamics, the study proposes a Knowledge Growth Dynamics Model that uses differential equations to represent knowledge development through collaborative and self-directed learning.

Keywords: Differential equations; ethnolinguistics; ethnomathematics; knowledge growth dynamics; problem-based learning; Sundanese culture

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INTRODUCTION

In an era of accelerating globalization, preserving and pedagogically integrating indigenous knowledge systems, including ethnomathematics, poses significant global challenges. Ethnomathematics research demonstrates that

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mathematics is not a culture-free discipline but rather a body of knowledge constructed through diverse traditional practices (D'Ambrosio, 1985; Powell & Frankenstein, 1997). In this context, mathematical thinking is profoundly shaped by linguistic, cultural, and sociocultural contexts (Planas & Pimm, 2023; Schiltz et al., 2024). This recognition has significant implications for language education: if mathematical thinking is culturally and linguistically embedded, language educators, particularly in multilingual settings, must understand this embeddedness (Moschkovich, 2007; Setati, 2005). Ethnomathematics offers authentic, context-rich content for content-based language instruction, fostering linguistic competence and intercultural awareness (Lyster, 2023; Stoller, 2022).

Despite growing international recognition, research on pedagogical transmission of ethnomathematics, particularly at the postgraduate level within language-focused programs, remains limited (Mabotja, 2025; Utami & Sagita, 2025). Most studies in this area concentrate on primary or secondary mathematics classrooms (Lidinillah et al., 2022; Supriadi, 2022). This gap is significant because postgraduate programs prepare curriculum developers, teacher educators, and cultural advocates who will determine whether and how indigenous mathematical knowledge is transmitted to future generations.

A second gap concerns the linguistic analysis of ethnomathematical knowledge. Recent ethnomathematics research has largely emphasized cultural practices, mathematical literacy, and the integration of indigenous knowledge into mathematics education (Kusuma et al., 2024; Pratama & Yelken, 2024). However, less attention has been given to how ethnomathematical knowledge is constructed through a functional linguistic perspective. This study addresses this gap by applying Systemic Functional Linguistics (SFL) and analyzing the ideational, interpersonal, and textual metafunctions. Such an approach moves beyond describing linguistic forms to examining how mathematical knowledge is represented, evaluated, and systematically organized through language (Fitriani & Pratiwi, 2024).

Central to the SFL framework in this study is the system of transitivity, the primary linguistic resource for realizing the ideational metafunction. In Halliday's systemic functional grammar, transitivity is not a property of verbs in the traditional grammatical sense but a semantic system that construes human experience of the world into a manageable set of process types (Halliday & Matthiessen, 2014). According to Halliday (1985), reality is made up of different kinds of processes: those of doing, happening, feeling, and being. The clause serves as how these processes are encoded, capturing both the process types themselves and the participants and circumstances that accompany them. This grammatical system of representation is called transitivity.

Halliday and Matthiessen (2014) identify six primary process types that constitute the transitivity system. Material processes represent physical actions and happenings, involving an Actor who acts and often a Goal affected by it. Mental processes represent the inner workings of consciousness, namely perception, cognition, and affection, requiring a Senser and a Phenomenon. Relational processes establish relationships between entities, either attributing qualities (Attributive mode) or identifying equivalences (Identifying mode), with participants labeled Carrier/Attribute or Token/Value respectively. Verbal processes encompass symbolic exchanges of meaning, typically involving a Sayer and a Receiver. Behavioral processes occupy a borderline area between material and mental processes, representing physiological and psychological behaviors such as breathing, smiling, or dreaming. Existential processes construe existence, most commonly realized through the "there is" construction, with a single participant termed the Existent.

The analytical value of transitivity lies in its capacity to reveal how language users construe experience and represent reality, including the agency attributed to different participants, the types of activities foregrounded, and the relationships established between entities. Within SFL, transitivity realizes the experiential dimension of the ideational metafunction by organizing experience through process types, participant roles, and circumstances. Recent applications of SFL continue to show that transitivity patterns provide a systematic way to examine how particular discourses construct participants, actions, events, and relationships (Darong & Regus, 2024; Xiong, 2024). For example, Darong and Regus (2024) demonstrate that transitivity analysis can be used to identify how experiential meanings are systematically constructed in educational texts, while Xiong (2024) illustrates how different process types can be related to broader ideational representations in discourse.

Importantly, transitivity choices are not merely formal or stylistic features. The choice of process types and participant configurations shapes how experience is linguistically organized and, consequently, how particular perspectives on events, actors, and relationships are foregrounded. Recent discourse studies have therefore continued to use transitivity as an analytical resource to examine representation and meaning construction across genres, including political discourse, literary texts, and educational materials (Anam et al., 2024; Darong & Regus, 2024). In educational discourse specifically, transitivity patterns can reveal what

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kinds of activities, participants, and relationships are foregrounded in pedagogical materials.

Applying transitivity analysis to ethnomathematical representation is particularly pertinent. When students document indigenous mathematical knowledge, their transitivity choices reveal how they construe mathematical processes: whether they represent astronomical events as animate actions (material processes such as *kidang turun kujang*) or as objective equivalences (relational processes such as *nyaéta*, *téh*, or the equals sign). These choices are not arbitrary but reflect culturally shaped ways of understanding and encoding mathematical relationships. The transitivity system thus provides an analytical apparatus for examining how ethnomathematical knowledge is linguistically constructed, complementing interpersonal and textual analyses that address modality and thematic organization, respectively.

As a multidisciplinary course that integrates linguistic, anthropological, and mathematical knowledge, ethnolinguistics requires pedagogical approaches that accommodate its complexity. Traditional lecture-based methods may not adequately engage students in the collaborative inquiry needed to understand the relationships among language, culture, and mathematical thinking. Indeed, ethnolinguistics has long focused on the relationships among language, culture, and cognition (Hymes, 1974; Duranti, 1997). Ethnolinguists argue that language is a fundamental medium for encoding and transmitting cultural knowledge (Sapir, 1921; Whorf, 1956). Different languages organize mathematical notions in culture-specific ways, reflecting different cognitive strategies (Lucy, 1992; Levinson, 2003; Everett, 2005). This linguistic relativity in mathematical thinking aligns with Whorf's (1956) hypothesis that language influences thought.

These relationships matter especially when mathematical knowledge is examined within specific linguistic and cultural communities. Language is not merely a neutral medium for expressing mathematical concepts; it can reflect culturally situated ways of classifying, counting, measuring, and conceptualizing mathematical relationships (Chrisomalis, 2021). From an ethnomathematical perspective, mathematical knowledge is embedded in cultural practices and local ways of understanding the world. The Sundanese context is particularly relevant because research has documented culturally specific mathematical practices involving estimation, measurement, pattern-making, and calendrical systems (Muhtadi et al., 2017; Prabawati & Muslim, 2022). Examining these linguistic and cultural resources can therefore provide insight into how mathematical knowledge is represented, transmitted, and understood within the Sundanese community.

Sundanese, an Austronesian language spoken by approximately 40 million people in West Java, possesses sophisticated linguistic systems for encoding numerical, spatial, and temporal concepts (Hardjadibrata, 1985). The language includes distinctive counting terms such as *salawe* (25) and *saeuheum* (infinite/countless) (Abdullah, 2017). Meanwhile, Umbara (2024) found numbers structured around multiples of 25 with unique characteristics for numbers 21–29. Beyond basic counting, Sundanese encodes complex concepts related to time and measurement, including the *pranata mangsa* time-reckoning system (Sudaryat, 2015) and measurement units such as *kibik* and *bata* (Muhtadi et al., 2017).

Researching ethnomathematics in the Sundanese cultural context is particularly valuable for the international research community because it brings a distinctive, relatively underrepresented cultural perspective to the study of mathematics and language. Sundanese cultural practices, linguistic resources, and traditional systems of measurement and calendrical knowledge provide opportunities to examine how mathematical ideas are shaped by local cultural knowledge (Muhtadi et al., 2017; Prabawati & Muslim, 2022). Such research can therefore contribute not only to the understanding of Sundanese ethnomathematics but also to broader international discussions on culturally situated mathematics education, linguistic diversity, and the relationship between language, culture, and mathematical knowledge.

In addition, teaching ethnomathematics within an ethnolinguistics course offers unique opportunities to bridge disciplines and deepen understanding of how language, culture, and mathematical thinking interact. Problem-Based Learning (PBL) has emerged as a robust pedagogical framework for addressing complex, interdisciplinary content. Grounded in constructivist learning theory, PBL posits that learners actively construct knowledge through engagement with authentic problems and social interaction (Barrows, 1996; Hmelo-Silver, 2004). Recent research demonstrates PBL's effectiveness in language education and in developing intercultural competence (Fielden Burns & Rico García, 2021; Al-Busaidi et al., 2021).

This study addresses three objectives: (1) examine postgraduate students' perceptions of PBL as a pedagogical approach for learning ethnomathematics within an ethnolinguistics course; (2) investigate how the students use SFL metafunctions, including transitivity choices within the ideational metafunction, in representing ethnomathematical knowledge; and (3) propose a conceptual framework, the Knowledge Growth Dynamics Model, that mathematically describes knowledge construction processes in PBL.

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METHOD

Research Design

This study used mixed methods, combining a qualitative case study with descriptive statistics, to examine postgraduate students' experiences with PBL in an ethnolinguistics course focused on ethnomathematics. The qualitative approach captured the richness of students' perceptions, learning processes, and outcomes in an authentic classroom context. Mathematical modeling using differential equations represented how the PBL approach contributes to knowledge acquisition over time. The study used multiple data sources, questionnaires, observations, and documentary analysis, to achieve triangulation.

Context and Participants

The study was conducted in a master's degree program at the Sundanese Department of a public university in Indonesia. The program offers an ethnolinguistics course that includes a module on ethnomathematics. The 23 participants were postgraduate students (17 female, 6 male, aged 22–35) formally enrolled in the course. Purposive sampling was employed to select students who (1) were enrolled in the ethnolinguistics course and (2) had completed prerequisite courses in linguistics and Sundanese cultural studies. They were divided into three groups and presented with three authentic problems:

- *Problem 1:* Numerical systems in rules, time, and size in Sundanese traditional practices
- *Problem 2:* Numerical systems in the ancient Sundanese manuscript *Sanghyang Siksa Kandang Ng Karesian* (1518 AD)
- *Problem 3:* Numerical systems in the *Palintangan* manuscript (traditional Sundanese astrology and calendrical calculation)

The five-week PBL process included problem introduction, group formation, brainstorming, literature review, data collection, analysis, synthesis, oral presentations, and final report submission.

All participants held bachelor's degrees, primarily in Sundanese language education or related fields. They had foundational knowledge of linguistics, Sundanese language and culture, and ethnolinguistics, but limited prior experience with PBL and ethnomathematics. They were selected because their background enabled them to engage with the course content while providing appropriate context for examining learning through PBL.

All participants provided written informed consent before participating in the study. They were fully informed about the research purpose, the procedures involved, the voluntary nature of their participation, and their right to withdraw at any time without academic or personal consequences. Confidentiality and anonymity were guaranteed throughout the study; all data were anonymized using pseudonyms or codes, and any identifying information was removed from the transcripts and reported findings.

Data Collection Instruments

Perception Questionnaire

A self-administered Likert-scale questionnaire comprising 12 statements was adapted from Munoz Campos (2017) to assess students' perceptions of PBL's contribution to cognitive development, reflective and critical thinking capacity, research skills, knowledge integration, social skills, self-directed learning, personal development, information literacy, problem authenticity, and relevance to teacher education.

Observations and Documentary Analysis

Systematic classroom observations were conducted throughout the five phases of the PBL process: (1) orienting students to the problem, (2) organizing students for learning, (3) guiding individual and group investigation, (4) developing and presenting solutions, and (5) analyzing and evaluating the problem-solving process. The PBL activities were designed around contextual problems requiring students to investigate ethnolinguistic and mathematical information rather than receive the relevant concepts directly from the facilitator.

During the problem-orientation phase, the facilitator spent about 15 minutes presenting an authentic contextual problem related to Sundanese cultural and linguistic practices and establishing the mathematical issue to be investigated. Rather than explaining the concepts needed to solve the problem, the facilitator used probing questions to help students identify what they already knew, what they did not yet know, and what information they needed to develop a solution.

The organization phase, approximately 15 minutes, involved forming collaborative groups, clarifying the problem-solving task, identifying preliminary subproblems, distributing responsibilities, and developing an initial investigation plan. Students were encouraged to formulate questions and identify the ethnolinguistic, mathematical, and contextual evidence they needed to collect. The facilitator monitored the process and clarified procedural issues without determining the solution or assigning specific answers.

The largest proportion of each session, approximately 70 minutes, was allocated to the individual and group investigation phase. Students searched for, selected, compared, and interpreted relevant technical and contextual literature to investigate the problem. They discussed the relationship between ethnolinguistic evidence and mathematical concepts, formulated possible explanations or solutions, and revised their initial interpretations as new evidence emerged.

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The groups were allocated approximately 30 minutes to develop and present solutions. Each group synthesized its investigation into a coherent solution and presented the relationship between the contextual evidence, ethnolinguistic interpretation, mathematical reasoning, and proposed solution. Other groups were invited to question the evidence, reasoning, and assumptions underlying the presented solution. The facilitator primarily moderated, prompting students to justify claims and respond to alternative interpretations rather than evaluating the solution immediately.

The final 20 minutes focused on analyzing and evaluating the problem-solving process. Students reflected on the adequacy of the evidence they used, the mathematical and ethnolinguistic reasoning they developed, the difficulties they encountered during the investigation, and the revisions they made to their initial ideas. The facilitator provided feedback on the quality of the reasoning and evidence and guided students in identifying how the problem-solving process could be improved in subsequent activities.

Thus, each PBL session lasted approximately 150 minutes, but the allocation was organized according to the PBL learning cycle rather than a conventional sequence of explanation, practice, and presentation. The duration of specific activities could be adjusted based on the problem's complexity and students' level of independence, while the five-phase PBL structure remained consistent across sessions.

Observation records focused on students' engagement in defining the problem, organizing group investigations, formulating investigative questions, selecting and evaluating technical literature, using contextual information, integrating ethnolinguistic and mathematical evidence, developing and justifying solutions, responding to alternative interpretations, and reflecting on the problem-solving process. The study evaluated student artifacts, including investigation notes, source-analysis records, group reports, presentation materials, and final reports, using a study-developed analytic rubric. The rubric assessed (1) problem identification and contextual understanding, (2) quality and relevance of supporting literature, (3) integration of ethnolinguistic and mathematical concepts, (4) appropriateness and justification of the proposed solution, and (5) clarity and coherence of the final product. Each criterion was rated on a 4-point scale, with higher scores indicating stronger evidence of the targeted PBL learning outcomes.

Documentary analysis was conducted on meeting minutes, interview transcripts, literature notes, presentation materials, and final reports. These documents were used to corroborate the observation findings and to trace changes in students' problem-solving, knowledge integration, research skills, and independent learning throughout the PBL process. Combining observations and documentary evidence allowed the researchers to examine not only students' reported perceptions but also observable learning processes and products.

Instrument Validity and Reliability

Content Validity: Three experts in ethnolinguistics, educational psychology, and Sundanese language education assessed the questionnaire's content validity. The Scale-Level Content Validity Index (S-CVI) was 0.89, indicating excellent content validity (Polit & Beck, 2006; Ayre & Scally, 2014).

Reliability: Cronbach's alpha coefficient was calculated using SPSS 18.0 based on responses from the 23 participants. The overall Cronbach's alpha for the 12-item questionnaire was $\alpha = 0.86$, indicating good internal consistency (DeVellis, 2017; Field, 2018; Nunnally & Bernstein, 1994). Corrected item-total correlations ranged from 0.43 to 0.74, exceeding the recommended threshold of 0.30 (Hair et al., 2019). Subscale reliability values ranged from 0.82 to 0.85, indicating acceptable to good internal consistency across all theoretical dimensions.

Data Analysis

Data were analyzed using descriptive statistics, qualitative analysis, SFL, and mathematical modeling. Questionnaire responses were analyzed using frequencies and percentages to identify students' perceptions of PBL across cognitive, reflective, collaborative, and self-directed learning dimensions.

Qualitative data from observations, meeting records, interview transcripts, literature notes, presentations, and final reports were analyzed thematically to identify patterns in students' learning processes, collaboration, problem-solving, and construction of ethnomathematical knowledge. Documentary data were also analyzed using an SFL framework to examine how students constructed and organized ethnomathematical knowledge through language. The analysis focused on the three metafunctions of language: (1) the ideational metafunction, particularly material and relational processes used to represent mathematical, cultural, and astronomical phenomena; (2) the interpersonal metafunction, particularly declarative mood and modality used to construe knowledge, certainty, and authority; and (3) the textual metafunction, particularly thematic progression and lexical cohesion used to organize information and establish textual coherence. The SFL analysis therefore examined not only what ethnomathematical knowledge students represented but also how they linguistically constructed, evaluated, and organized that knowledge.

Finally, the observed learning dynamics were translated into a mathematical model using differential equations. The model was necessary to formalize the PBL process mathematically by

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representing how students' knowledge develops over time as a function of collaborative interaction, self-directed learning, and other relevant learning factors. Thus, the model complemented the qualitative and SFL analyses by describing the dynamic relationships among these factors and their contribution to learning outcomes in the language curriculum.

FINDINGS

Postgraduate Students' Perceptions of the PBL Experience

As an initial finding, Table 1 shows that students completed a perception survey covering 12 statements about the use of PBL in the ethnolinguistics subject (specifically on the topic of ethnomathematics).

Table 1

Criteria and Percentages about Postgraduate Students' PBL Experience Perceptions

Item (adopted from Munoz Campos, 2017)		SA/A %	NA/ND %	D/SD %
1.	This PBL experience contributed to my cognitive development.	90	10	
2.	This PBL experience contributed to my reflective capacity.	91	5	4
3.	This PBL experience helped me develop my capacity for critical reflection.	93	7	
4.	This PBL experience strengthened my research skills.	77	20	3
5.	This PBL experience helped me integrate various types of knowledge.	82	12	6
6.	This PBL experience helped develop my social skills (interacting with others, teamwork, etc.).	77	20	3
7.	This PBL experience fostered control of my own learning	80	8	12
8.	This PBL experience contributed to my personality development.	64	16	20
9.	The PBL experience helped me develop my skills in searching for, analyzing, and synthesizing information.	85	5	10
10.	Although the problems were fictitious, they were very similar to "real problems"	70	30	
11.	PBL is a learning strategy that strengthens initial teacher education.	90	10	
12.	PBL is a learning strategy that strengthens initial teacher education.	83	12	5

Note. SA/A=Strongly Agree; NA/A=Neither Agree nor Disagree; D/SD=Disagree/Strongly Disagree

Table 1 shows the criteria and percentages corresponding to postgraduate students' perception levels. In the context of the tabulation process, the five criteria were grouped into three criteria: (a) and (b) together, (c), and (d) and (e) together. The results were calculated using SPSS. Overall, postgraduate students had a favorable perception of their engagement in using PBL in the ethnolinguistics subject across most criteria; most items fell into the Totally Agree/Agree category, with percentages ranging from 80% to 93%. Perceptions of PBL's contribution to developing their cognitive skills (Item 1) were rated very high (90%). Other items also rated very high; for example, their reflective capacity (Item 2), at 91%; their critical reflective capacity (Item 3), at 93%; their information searching, analytical, and synthesizing skills (Item 9) at 85%, as well as the contribution to the strengthening of their initial teacher education program (Item 11) at 90% should be underlined. However, the analysis showed that PBL's contribution to the development of students' personality (Item 8) was relatively low, at 64%.

Ethnomathematics Problem Solutions: A Systemic Functional Linguistic Analysis

The findings indicated that PBL positively influenced learning outcomes. Students demonstrated improved knowledge of ethnomathematics concepts and applied mathematical ideas to authentic cultural contexts. This section shows how students drew on SFL resources to represent their ethnomathematics work, using Halliday and Matthiessen's (2014) ideational (experiential), interpersonal, and textual metafunctions.

Group 1: Experiential Analysis of Numerical Systems in Rules, Time, and Size

Group 1 investigated Sundanese numerical expressions related to rules, time, and measurement systems.

Ideational Metafunction: Transitivity Analysis

For *Pranata Mangsa* (Seasonal Calendar), Table 2 shows that temporal expressions follow consistent grammatical patterns that use animal-movement processes as metaphors for astronomical events.

These expressions constitute experiential metaphor (Halliday, 1998), construing astronomical phenomena as animate, goal-directed actions and reflecting a Sundanese cultural conceptualization of celestial bodies as active agents. Temporal anchoring is realized through time circumstances (e.g., "24.00 hours on September 15"). For temporal lexicons, Table 3 displays that SFL analysis revealed systematic classification through verbal groups and nominal compounds.

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Table 2
Temporal Expressions Used by Group 1

Temporal Expression	Linguistic Process Type	Participant Configuration	English Gloss
Kidang turun kujang	Material (movement)	Actor: *kidang* (deer); Goal: *kujang* (kris)	'Deer descends the kris'
Kidang ngarangsang	Material (movement)	Actor: *kidang* (deer); Process: *ngarangsang* (to climb toward)	'Deer climbs toward'
Kidang mencrang	Material (spread)	Actor: *kidang* (deer); Process: *mencrang* (to spread/disperse)	'Deer disperses'
Kidang medang	Material (retreat)	Actor: *kidang* (deer); Process: *medang* (to withdraw/retreat)	'Deer retreats'

Table 3
Temporal Lexicons Used by Group 1

Temporal Expression	Grammatical Structure	Process Type	Meaning Encoding
Tengah Peuting	Nominal Compound	Relational (attributive)	'Midnight' - *tengah* (center/middle) + *peuting* (night)
Usum Tumorék	Verbal Nominalization	Material (process as thing)	'Early morning' - *usum* (season/time) + *tumorék* (to wake/emerge)
Janari Sapi	Possessive Nominal	Relational (possessive)	'Dawn' - *janari* (dawn) + sapi (cow) [cow's dawn]
Kongkorongok Hayam Dua Kali	Clausal Nominal	Material (process as circumstance)	'Second rooster crow' - Process + Temporal circumstance
Balébat	Single Lexeme	Material (nominalized)	'Early morning' - lexicalized time noun
Carangcang Tihang	Nominal Compound	Relational (metaphorical)	'Morning' - *carangcang* (?) + tihang (pillar/post)
Murag Ciibun	Verbal-Nominal Compound	Material (process as thing)	'Late morning' - *murag* (to fall) + *ciibun* (dew)
Lingsir Ngulon	Verbal-Adverbial Compound	Material (movement)	'Afternoon' - *lingsir* (to incline) + *ngulon* (westward)
Sareureuh Budak	Possessive Nominal	Relational (possessive)	'Children's rest time' - *sareureuh* (rest) + budak (children)
Peuting	Single Lexeme	Relational (existent)	'Night' - basic time noun

Linguistic Significance: Sundanese encodes time through multiple conceptual metaphors, namely time as location (*tengah peuting*), time as movement (*lingsir ngulon*), time as possession (*janari sapi*), and time as event (*kongkorongok hayam dua kali*), which align with Lakoff and Johnson's (1980) conceptual metaphor theory. For measurement units, SFL analysis revealed systematic encoding through nominal groups with embedded numerative and epithet functions.

Table 4
Measurement Unit Used by Group 1

Measurement Unit	Grammatical Function	Numerative	Thing	Linguistic Feature
Kibik	Measurement nominal	(implied)	unit of volume	Lexicalized from Dutch *kubiek* (cubic)
Bata	Measurement nominal	(implied)	unit of area	Lexicalized from bata (brick) - metonymic
sapuluh kibik	Numerative + Thing	*sa-puluh* (ten)	*kibik*	Quantifier + Measurement Nominal
dua bata	Numerative + Thing	*dua* (two)	*bata*	Quantifier + Measurement Nominal

The measurement terms form a lexical field of quantification differing from the SI system, revealing culture-specific conceptualizations of spatial extension and volume. Interpersonal Metafunction: The documentation revealed systematic use of declarative mood with high epistemic modality (realized through relational verbs such as *mangrupakeun*), construing the temporal system as objective, factual knowledge.

***Group 2: Interpersonal and Textual Analysis of Numerical Systems in* Sanghyang Siksa Kandang Ng Karesian**

Group 2 investigated the ancient Sundanese manuscript (1518 AD) and identified numerical concepts embedded in its moral and philosophical teachings.

Interpersonal Metafunction: Mood and Modality

As shown in Table 5, the manuscript's moral teachings primarily use relational processes realized

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through the declarative mood, construing moral categories as objective truths.

Deontic modality operates as a graded scale: high-value *kudu* (must) for fundamental moral principles; medium-value *kudu* (should) for ethical recommendations; low-value *bisa* (can) for potential outcomes.

Textual Metafunction: Thematic Structure

Theme-Rheme analysis revealed consistent thematic patterning. Table 6 depicts the theme structure.

Table 5

The Realization of Mood

Clause	Process Type	Mood	Function
Dasaindria nyaéta sapuluh indria	Identifying relational	Declarative	Defining the ten senses
Srota indria téh pangrungu	Attributive relational	Declarative	Assigning property (hearing)

Table 6

Thematic Structure Realization

Clause	Theme	Rheme	Thematic Progression
Dasaindria	*Dasaindria*	*nyaéta sapuluh indria*	Given (topic introduced)
Pancabudi indria	*Pancabudi indria*	*lima indria panca*	Given (elaboration)

The thematic structure follows a consistent pattern: Topical Theme (category name) in the Theme position; the Rheme provides definition/classification; parallel structure creates a taxonomic hierarchy. This realizes the textual metafunction through Given-New organization, lexical cohesion (repetition of *indria*), and structural parallelism.

Ideational Metafunction: Transitivity of Moral Principles

The *Dasamarga* (ten paths) employs predominantly relational (80%) and material (20%) processes. Relational processes dominate, construing moral qualities as attributes of the person (*ramah*: kind, *asih*: love, *karunya*: pity for), reflecting a state-oriented rather than action-oriented conceptualization of morality.

Group 3: Ideational and Textual Analysis of Numerical Systems in Palintangan Manuscript

Group 3 investigated the traditional Sundanese astrological and calendrical system.

Ideational Metafunction: Transitivity in Mathematical Calculations

In Table 7, mathematical processes are encoded through material processes (carrying out calculations) and relational processes (expressing mathematical relations).

Table 7

Temporal Expressions Used by Group 3

Clause	Process Type	Mathematical Function
"(5 × 354) + (3 × 355) = 2,835"	Material (calculation: multiplication, addition)	Computing days per *windu*
"*Saka* year = 354 3/8 days"	Identifying relational (“is equal to”)	Defining the *Saka* year
"1 *windu* = 8 years"	Identifying relational (“is equal to”)	Defining the 8-year cycle

Table 7 presents the temporal expressions Group 3 used to explain the mathematical calculation and chronological structure of the Saka calendar. The first clause, “(5 × 354) + (3 × 355) = 2,835,” represents a material process because it describes mathematical operations involving multiplication and addition to calculate the total number of days in one windu. The second expression, “Saka year = 354 3/8 days,” represents an identifying relational process, establishing the duration of a Saka year through an equation. Similarly, “1 windu = 8 years” functions as an identifying relational process, defining a windu as an eight-year cycle. Overall, these expressions demonstrate how Group 3 employs mathematical operations and relational equations to construct temporal meaning, combining numerical calculations with definitions of calendrical units.

Table 8 synthesizes the linguistic patterns identified across the three groups, showing how each group employs different linguistic resources to construct meaning through the ideational, interpersonal, and textual metafunctions.

Table 8

Synthesizing Linguistic Patterns

Metafunction	Group 1 (Time/Size)	Group 2 (Moral System)	Group 3 (Calendrical)
Ideational	Material processes; Relational processes	Relational processes; Behavioral processes	Relational processes; Material processes; Grammatical metaphor
Interpersonal	Declarative mood; High epistemic modality	Declarative mood; Deontic modality	Declarative mood; Technical certainty
Textual	Given-New progression; Lexical cohesion	Taxonomic Theme-Rheme; Lexical cohesion	Mathematical Theme-Rheme; Sequential conjunction

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At the ideational level, Group 1 predominantly uses material and relational processes to represent time and size through descriptions of physical phenomena and relationships between quantities. Group 2 relies mainly on relational and behavioral processes to represent its moral system by describing moral principles, states, and human conduct. Meanwhile, Group 3 combines relational and material processes with grammatical metaphor to explain calendrical concepts through mathematical relationships and computational operations. At the interpersonal level, all three groups predominantly use declarative mood to present information.

The Knowledge Growth Dynamics Model

Drawing on constructivist learning theory and dynamic systems approaches, this study proposes the Knowledge Growth Dynamics Model (KGDM), which mathematically describes how knowledge develops through PBL processes, informed by both theories and class observations.

$$\frac{dK}{dt} = \propto P(t) + \beta.\mathrm{I(t)} - \lambda \mathrm{K}$$

Where:

- K = student knowledge level at time t
- t = time spent learning (weeks)
- $P(t)$ = Problem-Based Learning function
- $I(t)$ = Independent (self-directed) Learning function
- α = effectiveness coefficient of PBL
- β = effectiveness coefficient of Independent Learning
- λ = knowledge decay (forgetting) coefficient

If we assume

$P(t)=P_0$ and $I(t)=I_0$,

where P_0 and I_0 are positive constants, then the model simplifies to

$$\frac{dK}{dt} = \propto P_0 + \beta.\mathrm{I}_0 - \lambda \mathrm{K}$$

To simplify the computation, let

$$\mathrm{A} = \propto P_0 + \beta.\mathrm{I}_0$$

Then the equation becomes

$$\frac{dK}{dt} = A - \lambda \mathrm{K}$$

$$\frac{dK}{dt} + \lambda \mathrm{K} = A$$

This type of ODE can generally be solved by multiplying both sides by $\mu(t) = e^{\int P(t)\,dt}$

$$\mu(t) = e^{\int P(t)\,dt} = e^{\int \lambda\,dt} = \mathrm{e}^{\lambda t}$$

Thus, the integrating factor is $\mathrm{e}^{\lambda t}$

Multiplying through

$$\mathrm{e}^{\lambda t}\frac{dK}{dt} + \lambda \mathrm{K} = A\mathrm{e}^{\lambda t}$$

By employing the reverse product rule, we obtain

$$\frac{d(\mathrm{e}^{\lambda t}K)}{dt} = A\mathrm{e}^{\lambda t}$$

Integrating both sides

$$\int d\left(e^{\lambda t}K\right) = \int Ae^{\lambda t}\,dt$$

$$e^{\lambda t}K = \frac{A}{\lambda}e^{\lambda t} + C$$

Solving for K(t)

$$K(t) = \frac{A}{\lambda} + Ce^{-\lambda t}$$

Let us substitute A with these two terms

$$\mathrm{A} = \propto P_0 + \beta.\mathrm{I}_0$$

$$K(t) = \frac{\propto P_0 + \beta.\mathrm{I}_0}{\lambda} + Ce^{-\lambda t}$$

Applying the initial condition

If $t = 0$

$K(0) = K_0$

Since if t = 0 and $e^{-\lambda t} = e^0 = 1$

We have

$$K_0 = \frac{\propto P_0 + \beta.\mathrm{I}_0}{\lambda} + C$$

$$C = K_0 - \frac{\propto P_0 + \beta.\mathrm{I}_0}{\lambda}$$

Therefore, the complete solution is as follows:

$$K(t) = \frac{\propto P_0 + \beta.\mathrm{I}_0}{\lambda} + (K_0 - \frac{\propto P_0 + \beta.\mathrm{I}_0}{\lambda})e^{-\lambda t}$$

Where

K_0 = the initial knowledge level at $t = 0$

The model predicts that higher values of the PBL effectiveness coefficient (α), greater engagement in self-directed learning (βI_0), or lower knowledge decay (λ) result in a higher long-term knowledge level.

DISCUSSION

PBL as a Pedagogical Framework for Ethnolinguistics Education

The findings show that PBL provides a conducive pedagogical framework for teaching ethnomathematics in an ethnolinguistics course. Strong positive perceptions across multiple dimensions-cognitive development, reflective capacity, critical thinking, knowledge integration, and information literacy- support theoretical claims about PBL's effectiveness in promoting meaningful learning (Barrows, 1996; Hmelo-Silver, 2004).

PBL's collaborative nature aligns with constructivist principles of learning, where learners actively construct knowledge through social interaction and engagement with authentic problems (Jarvis et al., 1998). Students' reports that PBL enhanced their ability to integrate diverse types of knowledge reflect ethnolinguistics' interdisciplinary nature and ethnomathematics as a topic within it. This finding is consistent with research by Hamdani et al. (2023), who found that PBL with ethnomathematics nuances effectively supports student learning.

The finding that 93% of students agreed PBL contributed to their critical reflective capacity is particularly significant, as critical reflection is essential for understanding the complex

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relationships between language, culture, and mathematical thinking. This supports previous research on PBL's effectiveness in developing higher-order thinking skills (Cindy et al., 2008; Schmidt et al., 2009).

Collaborative Learning and Communicative Competence in Ethnolinguistics

The emphasis on collaborative group work in PBL enhanced students' communicative competence in multiple ways. The requirement to discuss, debate, and negotiate meaning in small groups provided authentic opportunities for language use central to ethnolinguistic inquiry (Miccoli, 2003). Students reported that group work enhanced their motivation and confidence in sharing ideas, supporting research on the affective benefits of collaborative learning (Akdoğan et al., 2024).

The group work process in PBL differs from conventional small-group activities by requiring students to identify what they need to know; distribute tasks and responsibilities; integrate diverse information sources; co-construct knowledge; and present findings to an audience. This process reflects authentic professional practices in which linguists, educators, and cultural practitioners collaborate to address complex problems. The PBL experience thus prepares students for future professional roles requiring collaborative problem-solving, aligning with Fielden Burns and Rico García's (2021) finding that PBL enables students to develop intercultural and linguistic competences through teamwork.

Students' Use of SFL Metafunctions in Representing Ethnomathematical Knowledge

The SFL analysis of students' documentation reveals how postgraduate students systematically employed ideational, interpersonal, and textual metafunctions to represent their ethnomathematical findings. This section discusses the linguistic patterns identified across the three groups and their implications for ethnolinguistics education.

Ideational Metafunction: Encoding Ethnomathematical Concepts

The analysis demonstrates that students utilized ideational resources to construe different types of ethnomathematical knowledge through distinct process types and participant configurations. Students consistently employed material processes to represent astronomical phenomena in the *Pranata Mangsa* system. Expressions such as *Kidang turun kujang* ('Deer descends the kris'), *Kidang ngarangsang* (Deer climbs toward'), and *Kidang mmedang (*eer retreats') construe celestial events as animate, goal-directed actions. This grammatical choice reflects not merely reporting Sundanese cultural knowledge but adopting the cultural conceptualization itself, students represented astronomical events through the same experiential metaphors embedded in Sundanese linguistic practices (Halliday, 1998). By encoding constellations as Actors performing material processes, students demonstrated understanding that Sundanese culture conceptualizes celestial bodies as active agents rather than passive objects. This finding aligns with Lakoff and Johnson's (1980) conceptual metaphor theory, showing that students recognized and reproduced the metaphorical mappings through which Sundanese construe astronomical knowledge.

Across all groups, relational processes dominated students' documentation, particularly for definitional and classificatory knowledge. Students employed identifying relational processes (*nyaéta*, *téh*, '=') to define mathematical categories: *Dasaindria nyaéta sapuluh indria* ('The ten senses are ten senses'), *Saka year = 354 3/8 days*, *1 windu = 8 years*. Attributive relational processes (*téh... téh*) assigned properties: *Srota indria téh pangrungu* ('The hearing sense is hearing'), *Short years: 354 days*. The predominance of relational processes (80% in Group 2's moral taxonomy) indicates that students construed ethnomathematical knowledge as definitional and taxonomic rather than procedural. This grammatical choice reflects an understanding that ethnomathematics is not merely about performing calculations but about recognizing and articulating culturally embedded conceptual systems. Students represented Sundanese mathematical knowledge as *what things are*, their essential properties and classifications, rather than *what one does* with them. This finding supports the ethnolinguistic perspective that mathematical knowledge is constituted in language through relational structures that establish categories, equivalences, and taxonomies (Halliday & Matthiessen, 2014).

Group 3's documentation of calendrical calculations demonstrated extensive grammatical metaphor (Halliday, 1998), where mathematical operations were encoded as nominalized entities rather than verbal processes. Expressions such as "(5 × 354) + (3 × 355) = 2,835" and "42,524 days per 120 years" represent mathematical relations as nominal groups rather than clausal processes. This feature characterizes scientific and mathematical registers, where nominalization enables the construction of technical, specialized discourse.

Graded Deontic Modality for Moral Knowledge

Group 2's documentation of the *Sanghyang Siksa Kandang Ng Karesian* revealed systematic use of deontic modality to encode moral obligations. Students employed a graded scale: high-value *kudu* (must) for fundamental moral principles (*Kudu ngajaga indria*-"Must protect the senses"), medium-value *kudu* (should) for ethical recommendations, and low-value *bisa* (can) for potential outcomes.

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This graded modality system reflects the manuscript's own moral epistemology, where different types of moral knowledge carry different degrees of obligation.

By reproducing the deontic modality system in their documentation, students demonstrated understanding that Sundanese moral knowledge is not merely descriptive but prescriptive, it does not simply describe how things are but instructs how people should act. This finding aligns with Abdullah's (2017) research on ethnomathematics from a Sundanese cultural perspective, which emphasizes integrating numerical, moral, and linguistic categories in Sundanese knowledge systems.

Lexical Cohesion and Knowledge Domains

Students employed lexical cohesion devices to create coherent knowledge domains. Repetition of key terms (*indria* across the ten-sense system, *windu* across the calendrical system) created cohesive chains that signaled membership in a particular knowledge domain. Hyponymy relationships (*dasaindria* → *pancabudi indria* → *srota indria*) established taxonomic hierarchies. Meronymy relationships (*indria* → eyes, ears, nose) represented part-whole knowledge structures.

The systematic use of lexical cohesion demonstrates students' capacity to construct coherent textual representations of knowledge domains. Rather than presenting isolated facts, students organized their documentation as integrated knowledge systems where terms and concepts were explicitly connected through cohesive devices. This finding aligns with research on PBL's effectiveness in promoting knowledge integration (Dolmans et al., 2016; Schmidt et al., 2009) and suggests that SFL analysis can reveal how students achieve this integration through linguistic resources.

The Proposed Mathematical Model of Knowledge Growth Dynamics

The proposed mathematical model contributes to educational research by representing knowledge development as a dynamic process rather than a static outcome. While conventional PBL studies often evaluate learning through pre-test/post-test comparisons or between-group analyses (Chen et al., 2021), the differential equation conceptualizes knowledge as a state variable continuously influenced by acquisition, reinforcement, self-directed learning, and forgetting. This perspective is consistent with systems thinking in education, which views learning as an evolving process shaped by interacting factors (Jacobson et al., 2019).

The model integrates three complementary theoretical perspectives. The PBL effectiveness coefficient reflects the constructivist view that learners construct knowledge through authentic problem solving and collaborative inquiry (Dolmans et al., 2016; Savery, 2019), supported by evidence that PBL can improve critical thinking (Chen et al., 2021). The self-directed learning parameter represents learners' regulation of goals, progress, and learning activities, which has become increasingly important in technology-mediated environments (Morris, 2024; Yurdal & Toraman, 2023; Doo & Zhu, 2024; Zhu et al., 2022). The knowledge-decay term incorporates forgetting as a natural characteristic of memory and highlights the role of reinforcement and spaced retrieval in sustaining knowledge (Agarwal et al., 2021; Yang et al., 2021; Finotelli & Eustache, 2023). Thus, the model provides a unified quantitative representation of learning, learner autonomy, and knowledge retention.

Another contribution is its ability to represent knowledge dynamics over time. Unlike approaches that primarily describe relationships within a particular dataset, differential equation models can examine system behavior under different conditions. This is consistent with recent developments in knowledge tracing and learning analytics (Sghir et al., 2023). The model's equilibrium solution represents the long-term knowledge level achieved when instructional input, independent learning, and knowledge decay reach a stable balance. This perspective shifts attention from immediate achievement to the sustainability of learning, which is particularly relevant to higher education and lifelong professional learning (Grafström et al., 2025)

Pedagogically, the parameters provide an interpretable basis for instructional decision-making. A low PBL-effectiveness coefficient may indicate insufficient authenticity, collaboration, or scaffolding (Dolmans et al., 2016; Loyens et al., 2023), whereas a low self-directed learning contribution may indicate a need for greater support for autonomy, metacognition, and self-regulation (Kaşikçi & İzmirli, 2024). Conversely, a high knowledge-decay coefficient may signal the need for retrieval practice, spaced repetition, and cumulative review to strengthen long-term retention (Agarwal et al., 2021; Carpenter et al., 2022; Roediger & Pyc, 2012). The model therefore links mathematical parameters with actionable pedagogical considerations.

Finally, the model supports computational simulation of hypothetical instructional conditions. Once parameter values are empirically estimated, simulations can examine the potential long-term effects of strengthening PBL, increasing self-directed learning, or reducing knowledge decay before costly classroom interventions are undertaken. Computational modeling and system-dynamics approaches have increasingly been used to connect educational theory with instructional design (González-Velásquez et al., 2025; Chernikova et al., 2020). More broadly, the model contributes to

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educational modeling by integrating mathematical methods with pedagogical theory and learning analytics (Gašević et al., 2023; Wise & Shaffer, 2015). Because its parameters correspond directly to educational constructs, it offers a theoretically interpretable basis for explanation, prediction, and potential instructional optimization (Dawson et al., 2023; Deho et al., 2023).

Limitations and Future Research

This study has several limitations that should be acknowledged. First, the study involved 23 students at a single university, limiting generalisability to other contexts. Future research should examine PBL in ethnomathematics education across multiple institutions and with larger samples, enabling parameter estimation for the KGDM. Second, the five-week PBL implementation was relatively brief. Future research should examine longer-term PBL implementations to assess whether benefits persist over time and to validate the model's predictions about temporal dynamics. Third, while the study examined perceptions and documented learning products, standardized assessment of learning outcomes would provide additional evidence of PBL's effectiveness. Future research should incorporate pre- and post-tests of ethnomathematics knowledge to estimate model parameters empirically. The study also did not include a comparison group, limiting conclusions about PBL's relative effectiveness compared to other pedagogical approaches. Future research should compare PBL with lecture-based and other active learning approaches to estimate parameter differences between approaches. Lastly, the KGDM proposed in this study is a theoretical framework that requires empirical validation. Future research should design studies to estimate the model's parameters and test its predictions empirically in ethnolinguistics contexts.

CONCLUSION

This study examined postgraduate students' perceptions of PBL in an ethnolinguistics course focused on ethnomathematics, investigated how students used SFL metafunctions to represent ethnomathematical knowledge, and proposed a mathematical model of knowledge growth during PBL. The findings show that PBL effectively teaches interdisciplinary content in postgraduate ethnolinguistics education. Overall, students reported highly positive perceptions of PBL across multiple dimensions. Students rated cognitive development at 90%, reflective capacity at 91%, critical thinking at 93%, knowledge integration at 82%, and information literacy at 85%. These results support theoretical claims about PBL's effectiveness in promoting meaningful learning.

The SFL analysis revealed that students systematically employed three metafunctions in their documentation. Using the ideational metafunction, students used material processes such as *kidang turun kujang* to construe astronomical events as animate actions, and relational processes such as *nyaéta, téh*, and the equals sign to encode mathematical equivalences as objective facts. Through interpersonal metafunctions, students employed declarative mood with high epistemic modality for factual knowledge and deontic modality (*kudu*) for moral obligations, thereby establishing authoritative knowledge transmission. Through textual metafunctions, students utilized thematic progression following a Given-New organization and lexical cohesion through repetition of *indria* and *dasa-* compounds to systematically structure taxonomic and mathematical knowledge.

Students also successfully documented complex Sundanese mathematical systems, including calendrical calculations known as *Palintangan*, measurement systems such as *kibik* and *bata*, moral classification systems termed *dasaindria*, and time-reckoning practices called *pranata mangsa*. This demonstrates their capacity to integrate linguistic, anthropological, and mathematical knowledge. PBL successfully integrated cultural knowledge into formal education, as students engaged with primary sources, documented traditional knowledge, and built capacity for culturally responsive pedagogy.

Through SFL-informed analysis, students developed a deeper understanding of the relationships between language, culture, and mathematical thinking. They gained insight into how the Sundanese language encodes culturally specific mathematical knowledge through grammatical resources such as classifiers (*dasa-*, *panca*), metaphorical mappings of time as movement, location, or event, and specialized mathematical registers. As a conceptual framework, the Knowledge Growth Dynamics Model mathematically formalizes knowledge construction in PBL, integrating key theoretical constructs of collaborative and self-directed learning while generating testable predictions for future research in ethnolinguistics education.

In conclusion, PBL provides a conducive pedagogical framework for teaching ethnomathematics in postgraduate ethnolinguistics education. Integrating Sundanese cultural knowledge, mathematical thinking, and linguistic analysis through PBL promotes deep learning while supporting the preservation of cultural knowledge. The SFL analysis shows that students not only acquired ethnomathematical content but also developed sophisticated linguistic resources to represent this knowledge across ideational, interpersonal, and textual dimensions. As education systems increasingly recognize the importance of

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culturally and linguistically responsive pedagogy, approaches such as PBL that support the integration of linguistic, cultural, and academic knowledge will become increasingly valuable.

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CONTRIBUTION OF THE AUTHORS

The first author contributed to conceptualization, research design, and preparation of the original manuscript draft. The second author developed the research instruments and identified and reviewed relevant literature and references. The third author conducted the data analysis and contributed to examining the research findings. The fourth author contributed to interpreting the findings and critically reviewed and revised the manuscript to improve clarity and coherence. The fifth author translated and proofread the manuscript to ensure linguistic accuracy, clarity, and consistency. All authors reviewed and approved the final version of the manuscript.

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