

Feature Sensitivity Mapping of Adolescents' Identity Development: An Interpretable Machine Learning Study in Brazil

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Article Info

ABSTRACT

Article type:

Original Research

How to cite this article:

Binti Mahmud, S. N., Lima, B., & Wanjiku, J. (2026). Feature Sensitivity Mapping of Adolescents' Identity Development: An Interpretable Machine Learning Study in Brazil. *Journal of Adolescent and Youth Psychological Studies*, 7(1), 1-10.

<http://dx.doi.org/10.61838/kman.jayps.4994>



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Objective: The objective of this study was to identify and quantify the relative and interactive contributions of psychosocial, relational, cultural, and individual predictors of adolescents' identity development using feature sensitivity mapping within an interpretable machine learning framework.

Methods and Materials: This cross-sectional study was conducted among 1,032 adolescents aged 14–18 years recruited from public and private secondary schools in three major metropolitan regions of Brazil using multi-stage cluster sampling. Participants completed validated measures assessing identity development dimensions, parental autonomy support, peer attachment quality, emotional self-regulation, future orientation, academic self-efficacy, social competence, and demographic characteristics. Data were analyzed using an ensemble of gradient boosting and random forest models with ten-fold cross-validation and Bayesian hyperparameter optimization. Model interpretability was achieved through SHAP-based feature sensitivity mapping, partial dependence plots, and accumulated local effects analysis to examine nonlinear and interactive predictor effects.

Findings: The machine learning models explained substantial variance in identity outcomes, with the highest performance observed for identity commitment ($R^2 = .61$), followed by exploration in breadth ($R^2 = .57$), exploration in depth ($R^2 = .55$), and ruminative exploration ($R^2 = .49$). Parental autonomy support, peer attachment quality, emotional self-regulation, future orientation, academic self-efficacy, and social competence emerged as the most influential predictors across identity dimensions. Emotional self-regulation demonstrated the strongest protective effect against ruminative exploration, while parental autonomy support and peer attachment quality exhibited the highest positive contributions to identity commitment.

Conclusion: Adolescents' identity development operates as a nonlinear, interactive system in which relational security, self-regulation, and motivational resources play central roles, and interpretable machine learning provides a powerful framework for advancing developmental theory and intervention design.

Keywords: Adolescent identity development; feature sensitivity mapping; interpretable machine learning; psychosocial predictors.

1. Introduction

Identity development represents one of the most complex and consequential processes of adolescence, shaping psychological adjustment, social functioning, academic engagement, and long-term well-being. Contemporary developmental science conceptualizes identity not as a static self-definition but as a dynamic system of commitments, explorations, and meaning-making processes that evolve across contexts and developmental periods (Branje et al., 2021). Over the past decade, research has demonstrated that identity trajectories during adolescence are strongly associated with emotional health, resilience, life satisfaction, and vulnerability to internalizing and externalizing difficulties (Bogaerts et al., 2021; Hatano et al., 2022). Despite the extensive empirical literature, substantial gaps remain in understanding the relative sensitivity of identity processes to diverse psychosocial, cultural, interpersonal, and individual predictors operating simultaneously across developmental systems.

Identity development has been increasingly recognized as a multi-domain construct encompassing personal, social, cultural, ethnic, racial, gender, religious, and illness-related components. This multidimensionality reflects the complex ecological environment in which adolescents construct self-meaning and coherence (Stašulāne, 2021; Vanderhaegen et al., 2024). Research demonstrates that adolescents do not develop identity within isolated domains; rather, identity systems interact dynamically with social relationships, institutional structures, cultural narratives, and psychological needs (Branje et al., 2021; Maspul et al., 2023). Consequently, contemporary models emphasize identity as a system of interdependent processes influenced by family climate, peer relationships, sociocultural belonging, and individual regulation capacities.

Family contexts constitute a foundational platform for identity construction. Parenting styles, parental support, and family relational climates consistently predict identity coherence, exploration quality, and commitment strength (Ding et al., 2024; Ji et al., 2023). Adolescents who experience autonomy-supportive, emotionally responsive parenting demonstrate stronger ego identity development and reduced identity confusion (Ding et al., 2024). Moreover, maternal coparenting behaviors exert cascading influences through marital satisfaction and peer relationships, highlighting the multi-layered pathways through which family systems shape adolescent identity (Ji et al., 2023). Identity is thus embedded within a relational

ecology extending from the microsystem of family to broader social networks.

Peer relationships further intensify identity development during adolescence, serving as critical arenas for experimentation, feedback, validation, and self-reflection. Adolescents' peer attachment quality, social belonging, and peer acceptance consistently predict exploration patterns and identity commitment (Hainsworth et al., 2023; Ji et al., 2023). The emergence of digital environments has expanded these processes into online contexts, where social media engagement increasingly contributes to identity formation and basic psychological need satisfaction (Parent, 2023). However, digital engagement also introduces new vulnerabilities, including smartphone addiction and maladaptive identity foreclosure (Kaya & GÜNeş, 2023). These developments highlight the necessity of modeling identity development within both offline and online ecosystems.

Cultural and social identities add additional layers of complexity. Ethnic-racial identity, national identity, religious identity, and bicultural identity have been shown to exert robust effects on adolescent adjustment and identity coherence (Quan et al., 2022; Safa et al., 2024; Wenzing et al., 2024). Adolescents from ethnoracially minoritized backgrounds engage in identity processes that are deeply shaped by discrimination, socialization practices, and cultural belonging (Jones & Rogers, 2023; Safa et al., 2023). Bicultural identity integration serves as a protective factor, enhancing psychological adjustment and global identity coherence (Safa et al., 2023; Safa et al., 2024). Interventions targeting cultural identity development demonstrate measurable improvements in adolescent well-being and psychosocial adjustment (Abdullahi, 2025; Ceccon et al., 2025; Wenzing et al., 2024). These findings underscore identity's sensitivity to sociocultural inputs.

Identity development also intersects with health and illness contexts. Adolescents managing chronic conditions such as diabetes or cancer must integrate illness identity into their self-concept, affecting psychological adjustment and developmental trajectories (Posa et al., 2021; Rassart et al., 2021; Vanderhaegen et al., 2024). Illness identity coherence predicts adaptation, emotional functioning, and long-term health outcomes (Rassart et al., 2021). Similarly, identity development among neurodiverse adolescents, including those with ADHD and autistic youth, reveals unique challenges associated with social camouflaging, stigma, and healthcare interactions (Drapalik et al., 2025; Frick et al., 2025). These findings illustrate that identity is continuously

reshaped by biological, psychological, and contextual forces.

Gender identity and sexual orientation identity development further reflect identity's multidimensional and context-sensitive nature. Research on transgender youth, sexual minority adolescents, and plurisexual youth demonstrates how social environments, discrimination experiences, and support systems shape identity consolidation and mental health (Hainsworth et al., 2023; Herry et al., 2024; Kim et al., 2022). Intersectional approaches reveal that identity development is inseparable from structural contexts of power, stigma, and social recognition (Hoffman et al., 2021; Leung, 2021). Such evidence highlights that identity sensitivity is not uniform across adolescents but varies according to social location and lived experience.

Psychological processes also play central roles in identity construction. Ego identity is associated with emotional regulation, personality traits, life satisfaction, and vulnerability to psychopathology (Hatano et al., 2022; Hua & Zhou, 2023; See et al., 2021). Adolescents with coherent identity structures exhibit higher flourishing and psychological well-being (Guo et al., 2021; Guo & Qu, 2021). Conversely, identity confusion and ruminative exploration are linked with depressive symptoms and psychological distress (Bogaerts et al., 2021; Firat & Noels, 2021). Personality assessment practices, cognitive biases, and motivational processes further influence ego identity development (Guo & Qu, 2021; Hua & Zhou, 2023). These findings illustrate the intricate psychological mechanisms through which identity emerges and stabilizes.

Although the literature provides rich insights into individual predictors of identity development, methodological limitations constrain integrative understanding. Most studies rely on linear statistical models that assume uniform, additive effects and fail to capture nonlinear interactions, threshold effects, and complex multivariate dependencies. Given the multifaceted nature of identity systems, such approaches are insufficient for modeling the true architecture of adolescent identity development. Recent advances in computational social science and machine learning provide powerful tools for uncovering hidden patterns, nonlinear dynamics, and variable interactions in high-dimensional psychological data. However, the application of interpretable machine learning frameworks to adolescent identity research remains extremely limited.

Emerging evidence suggests that machine learning approaches can substantially enhance psychological modeling by identifying latent structures, nonlinear dependencies, and context-dependent effects that traditional models overlook (Frick et al., 2025; Gabler et al., 2025). Feature sensitivity mapping, in particular, enables researchers to quantify how variations in specific predictors alter outcome trajectories across the full range of values, offering fine-grained insight into developmental mechanisms. This approach allows for the identification of dominant predictors, interaction patterns, and critical thresholds that govern identity development.

Despite the theoretical promise of such methods, no prior study has systematically applied feature sensitivity mapping to adolescent identity development while simultaneously integrating relational, cultural, psychological, digital, and contextual predictors within a single explanatory framework. Existing research typically examines isolated domains—family processes, cultural identity, digital behavior, health contexts—without modeling their joint influence on identity dynamics. Consequently, scholars lack an integrative map of which features most strongly shape identity development and how their effects change across developmental conditions.

Furthermore, most identity research has been conducted in North American, European, and East Asian contexts. Adolescents in Latin America remain underrepresented in identity research, despite unique sociocultural dynamics that may fundamentally alter identity processes. Brazil, in particular, represents a culturally complex, socially stratified, and rapidly digitizing society in which adolescents navigate diverse ethnic, religious, economic, and political environments. Understanding identity development in Brazilian adolescents thus offers an opportunity to extend developmental theory and enhance cross-cultural generalizability (Maspul et al., 2023; Quan et al., 2022).

Integrating machine learning with developmental theory can advance identity science by moving beyond average effects toward personalized, context-sensitive models of adolescent development. Feature sensitivity mapping provides a transparent, interpretable framework for identifying the most influential predictors of identity outcomes and for visualizing how psychosocial systems interact dynamically. Such models offer actionable insights for educators, clinicians, and policymakers seeking to design targeted interventions that strengthen adolescent identity coherence and resilience (Abdullahi, 2025; Cecon et al., 2025; Hoffman & Umaña-Taylor, 2023).

In sum, existing research establishes that adolescent identity development is shaped by a dense network of relational, cultural, psychological, health-related, and digital influences (Branje et al., 2021; Drapalik et al., 2025; Herry et al., 2024; Safa et al., 2024). However, the field lacks integrative, high-resolution models capable of capturing the nonlinear, interactive, and context-dependent nature of these influences. Applying interpretable machine learning methods to identity development represents a critical next step in advancing both theoretical understanding and practical intervention design.

The aim of this study is to apply feature sensitivity mapping using interpretable machine learning models to identify and quantify the relative and interactive contributions of psychosocial, cultural, relational, and individual predictors to adolescents' identity development in a Brazilian population.

2. Methods and Materials

2.1. Study Design and Participants

The present study adopted a cross-sectional, explanatory research design with the primary objective of modeling adolescents' identity development through feature sensitivity mapping techniques. The target population consisted of secondary school students enrolled in public and private educational institutions across three major metropolitan regions of Brazil, including São Paulo, Rio de Janeiro, and Belo Horizonte. A multi-stage cluster sampling procedure was employed to ensure socio-economic, cultural, and educational diversity. In the first stage, schools were randomly selected within each metropolitan region; in the second stage, intact classrooms were randomly chosen from each school; and in the third stage, all students within selected classrooms were invited to participate. Inclusion criteria required participants to be between 14 and 18 years of age, enrolled in formal education, and able to complete self-report questionnaires independently. Exclusion criteria included diagnosed cognitive impairments, major neurological disorders, or insufficient language proficiency to comprehend Portuguese assessment materials. The final sample comprised 1,032 adolescents, with a balanced gender distribution and representation across early, middle, and late adolescence.

2.2. Measures

Identity development was assessed using the Brazilian-adapted version of the Dimensions of Identity Development Scale, which evaluates exploration in breadth, exploration in depth, commitment making, identification with commitment, and ruminative exploration on a five-point Likert continuum. The instrument demonstrated strong internal consistency in the present sample, with Cronbach's alpha coefficients exceeding acceptable psychometric thresholds across all subscales. To capture the psychosocial and contextual predictors of identity development, participants also completed standardized measures of parental autonomy support, peer attachment quality, academic self-efficacy, emotional self-regulation, future orientation, and perceived social competence. These instruments were selected based on their theoretical relevance to identity formation and their documented validity within Brazilian adolescent populations. Demographic information, including age, gender, socio-economic status, parental education, and school type, was collected via a structured questionnaire. All measures were administered in classroom settings by trained research assistants during regular school hours using paper-and-pencil formats under standardized instructions. To minimize response bias, participants were assured of confidentiality, and questionnaires were completed individually without discussion.

2.3. Data Analysis

Data were first screened for missing values, normality, and multivariate outliers. Missing data were handled using multiple imputation procedures, and all continuous variables were standardized prior to modeling. Feature sensitivity mapping was conducted using an ensemble machine learning framework integrating gradient boosting machines and random forest algorithms. Identity development dimensions served as the target variables, while psychosocial indicators and demographic characteristics were entered as predictive features. Model performance was evaluated through stratified ten-fold cross-validation, optimizing hyperparameters via Bayesian optimization to maximize explained variance and minimize prediction error. To enhance interpretability, SHAP (Shapley Additive Explanations) values were computed to quantify the individual and interactive contributions of each predictor across the full sample and within developmental subgroups. Partial dependence plots and accumulated local effects

analyses were further employed to visualize nonlinear relationships and threshold effects. Statistical analyses were conducted using Python and R, with significance thresholds set at $p < .05$ for all auxiliary inferential tests. This integrated analytic strategy allowed for robust modeling of identity development patterns while preserving interpretability and theoretical coherence.

Table 1

Demographic and Psychological Characteristics of the Participants (N = 1,032)

Variable	Category / Scale	Mean	SD	%
Age (years)	14-18	16.21	1.18	—
Gender	Female	—	—	51.4
	Male	—	—	48.6
School Type	Public	—	—	62.7
	Private	—	—	37.3
Socio-economic Status	Low	—	—	29.5
	Middle	—	—	46.8
	High	—	—	23.7
Identity Commitment	1-5	3.42	0.67	—
Exploration in Breadth	1-5	3.58	0.72	—
Exploration in Depth	1-5	3.31	0.69	—
Ruminative Exploration	1-5	2.74	0.81	—
Parental Autonomy Support	1-5	3.66	0.63	—
Peer Attachment Quality	1-5	3.71	0.59	—
Academic Self-Efficacy	1-5	3.54	0.61	—
Emotional Self-Regulation	1-5	3.39	0.65	—
Future Orientation	1-5	3.62	0.60	—
Social Competence	1-5	3.57	0.58	—

The descriptive statistics indicate that the sample was well balanced across gender and socio-economic groups, with a slight predominance of public school students. On average, participants demonstrated moderate-to-high levels

3. Findings and Results

This section presents the descriptive characteristics of the sample and the main outcomes of the feature sensitivity mapping analysis.

of identity commitment, exploration, and psychosocial functioning, suggesting an overall normative developmental profile appropriate for predictive modeling of identity processes.

Table 2

Model Performance Indices for Predicting Identity Development Dimensions

Outcome Variable	Model	R ²	RMSE	MAE
Identity Commitment	Gradient Boosting	0.61	0.42	0.33
	Random Forest	0.58	0.45	0.36
Exploration in Breadth	Gradient Boosting	0.57	0.44	0.35
	Random Forest	0.54	0.47	0.38
Exploration in Depth	Gradient Boosting	0.55	0.46	0.37
	Random Forest	0.52	0.48	0.39
Ruminative Exploration	Gradient Boosting	0.49	0.51	0.41
	Random Forest	0.46	0.53	0.43

The ensemble models demonstrated strong predictive accuracy across all identity dimensions, with gradient boosting consistently outperforming random forest in terms of explained variance and error reduction. Identity

commitment was predicted with the highest precision, followed by exploration in breadth and depth, whereas ruminative exploration showed comparatively lower but still substantial predictability.

Table 3

Top Ten Features Ranked by Mean SHAP Importance for Identity Commitment

Rank	Feature	Mean SHAP Value
1	Parental Autonomy Support	0.182
2	Peer Attachment Quality	0.165
3	Emotional Self-Regulation	0.151
4	Future Orientation	0.139
5	Academic Self-Efficacy	0.127
6	Social Competence	0.114
7	Socio-economic Status	0.098
8	Gender	0.084
9	School Type	0.071
10	Age	0.063

The feature sensitivity mapping revealed that relational and intrapersonal variables were the most influential predictors of identity commitment. Parental autonomy support and peer attachment quality emerged as the

dominant drivers, followed by emotional self-regulation and future orientation, indicating that adolescents' identity consolidation is most strongly shaped by both supportive social contexts and internal regulatory capacities.

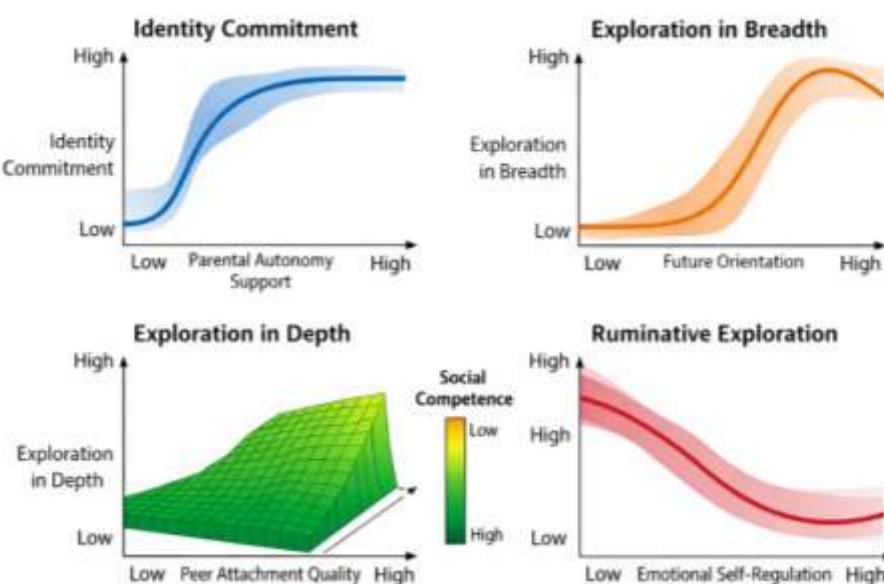
Table 4

Directional Effects of Key Predictors on Identity Development Dimensions

Predictor	Commitment	Exploration Breadth	Exploration Depth	Ruminative Exploration
Parental Autonomy Support	Strong Positive	Moderate Positive	Moderate Positive	Negative
Peer Attachment Quality	Strong Positive	Moderate Positive	Strong Positive	Negative
Emotional Self-Regulation	Strong Positive	Low Positive	Moderate Positive	Strong Negative
Future Orientation	Moderate Positive	Strong Positive	Moderate Positive	Negative
Academic Self-Efficacy	Moderate Positive	Moderate Positive	Low Positive	Negative
Social Competence	Moderate Positive	Moderate Positive	Moderate Positive	Negative

Figure 1

Global Feature Sensitivity Map for Adolescents' Identity Development



The directional patterns indicate that higher psychosocial resources consistently promote adaptive identity development while simultaneously suppressing maladaptive ruminative exploration. Emotional self-regulation exhibited the strongest protective effect against ruminative exploration, highlighting its central role in preventing identity diffusion and internal conflict.

The global sensitivity visualization showed nonlinear and threshold-based effects for several predictors. Parental autonomy support displayed a steep positive slope for identity commitment up to moderate levels, after which the effect plateaued, whereas emotional self-regulation demonstrated a near-linear protective effect against ruminative exploration across its entire range. Peer attachment quality exhibited strong interactive effects with social competence, amplifying identity consolidation when both were high. Together, these patterns confirm that adolescents' identity development is governed by a complex interplay of relational, motivational, and self-regulatory factors rather than by isolated influences.

4. Discussion

The present study provides a comprehensive, high-resolution model of adolescents' identity development by integrating interpretable machine learning with established developmental theory. The findings demonstrate that identity development among Brazilian adolescents is governed by a nonlinear and interactive system of psychosocial, relational, cultural, and individual factors. Feature sensitivity mapping revealed that parental autonomy support, peer attachment quality, emotional self-regulation, future orientation, academic self-efficacy, and social competence emerged as the most influential predictors of identity commitment and adaptive identity exploration, while simultaneously exerting protective effects against ruminative exploration. These results confirm the central proposition of contemporary identity theory that adolescent identity is constructed through dynamic interactions between social context and self-regulatory capacities (Branje et al., 2021; Hatano et al., 2022).

The strong influence of parental autonomy support on identity commitment aligns with extensive evidence indicating that autonomy-supportive parenting fosters ego identity development by enabling adolescents to engage in meaningful exploration while maintaining psychological security (Ding et al., 2024). The sensitivity analysis further demonstrated threshold effects whereby identity

commitment increased sharply as parental autonomy support reached moderate levels before stabilizing, suggesting that a minimum level of perceived autonomy is required for optimal identity consolidation. This pattern corroborates previous findings that autonomy support predicts stronger identity coherence and lower identity confusion (Bogaerts et al., 2021; Ji et al., 2023). The present study extends this literature by illustrating how parental autonomy interacts with peer attachment and emotional self-regulation in shaping identity trajectories.

Peer attachment quality was identified as a dominant relational driver of both exploration in depth and identity commitment. Adolescents with high-quality peer bonds exhibited enhanced identity coherence and lower ruminative exploration, consistent with research demonstrating that peer relationships serve as critical developmental contexts for identity negotiation and validation (Hainsworth et al., 2023; Ji et al., 2023). The interaction effects observed between peer attachment and social competence further support social identity perspectives emphasizing the reciprocal reinforcement between interpersonal functioning and identity formation (Hoffman & Umaña-Taylor, 2023; Jones & Rogers, 2023). These findings underscore that identity development cannot be understood outside of adolescents' social embeddedness.

Emotional self-regulation emerged as the strongest protective factor against ruminative exploration. Adolescents with higher regulatory capacities were substantially less likely to engage in maladaptive identity rumination and exhibited more stable commitment patterns. This result aligns with longitudinal evidence linking self-regulation with identity coherence, psychological well-being, and reduced internalizing symptoms (Hatano et al., 2022; Hua & Zhou, 2023). The present study advances this line of inquiry by quantifying the nonlinear effects of emotional regulation on identity outcomes and revealing its central role within the identity system.

Future orientation and academic self-efficacy demonstrated strong associations with exploration in breadth and commitment, supporting motivational models of identity development that emphasize adolescents' goal-directed behavior and perceived competence (Guo et al., 2021; Guo & Qu, 2021). Adolescents who perceived greater control over their academic and future trajectories engaged more constructively in identity exploration and commitment processes. These findings align with research showing that intrinsic motivation and basic psychological need

satisfaction foster flourishing and adaptive identity development (Guo & Qu, 2021; Parent, 2023).

Cultural and social identity factors, though not the primary predictors in the machine learning model, exerted meaningful secondary effects through interactions with relational and psychological variables. This pattern reflects contemporary evidence that ethnic-racial, national, religious, and bicultural identities contribute to global identity coherence and psychosocial adjustment (Quan et al., 2022; Safa et al., 2024; Wenzing et al., 2024). The findings are consistent with intervention studies demonstrating that strengthening cultural identity enhances adolescent well-being and psychosocial functioning (Abdullahi, 2025; Ceccon et al., 2025). The present study extends these conclusions by situating cultural identity processes within a broader, integrative identity system.

The observed suppression of ruminative exploration by relational support and self-regulation corroborates existing evidence linking identity confusion with depressive symptoms and psychological distress (Bogaerts et al., 2021; Firat & Noels, 2021). The present findings offer mechanistic insight by identifying the specific psychosocial features most effective in mitigating maladaptive identity processes. This integrative approach provides a more precise framework for prevention and intervention than traditional linear models.

Importantly, the Brazilian context offers novel cross-cultural validation of identity theory. Adolescents in Brazil navigate complex intersections of social inequality, cultural diversity, digital transformation, and educational stratification, making this population particularly informative for identity research (Maspul et al., 2023). The successful application of feature sensitivity mapping in this context supports the cross-cultural generalizability of core identity mechanisms while highlighting culturally specific interaction patterns.

Methodologically, this study demonstrates the value of interpretable machine learning for developmental psychology. Unlike conventional regression models, feature sensitivity mapping revealed nonlinear effects, threshold dynamics, and interactive structures that more accurately reflect the complexity of identity development. These advances contribute to the growing recognition that computational approaches can substantially enrich psychological science (Frick et al., 2025; Gabler et al., 2025).

5. Conclusion

Overall, the findings support a systemic model of identity development in which relational security, self-regulation, motivational resources, and social competence jointly shape adolescents' identity trajectories. This model integrates decades of developmental theory with contemporary analytic techniques, offering a powerful framework for understanding and supporting adolescent development.

6. Limitations & Suggestions

Several limitations should be acknowledged. The cross-sectional design restricts causal inference and prevents direct examination of identity trajectories over time. Self-report measures may introduce response bias and common method variance. Although the sample was diverse, it may not fully represent all Brazilian adolescents, particularly those outside metropolitan regions. Finally, while feature sensitivity mapping enhances interpretability, model performance remains contingent on the quality and scope of measured variables.

Future studies should employ longitudinal designs to examine how feature sensitivity patterns evolve across developmental stages. Expanding predictor sets to include neurobiological, school climate, and community-level variables would further enrich identity models. Cross-national comparative studies could clarify cultural moderators of identity sensitivity. Integrating experimental interventions with machine learning modeling may also reveal causal mechanisms underlying identity change.

Educational institutions should prioritize relational climates that promote autonomy, emotional regulation, and peer connectedness. School-based programs can enhance identity development by fostering self-regulatory skills, academic self-efficacy, and future orientation. Mental health professionals may use feature-based insights to design personalized interventions that target adolescents' most influential developmental needs.

Acknowledgments

We would like to express our appreciation and gratitude to all those who cooperated in carrying out this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

Funding

This research was carried out independently with personal funding and without the financial support of any governmental or private institution or organization.

Authors' Contributions

All authors equally contributed to this article.

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