KMAN PUBLISHING INSTITUTE
Journal Website

Article history:
Received 18 September 2025
Revised 04 February 2026
Accepted 16 February 2026
Published online 01 May 2026

Journal of Adolescent and Youth Psychological Studies

Volume 7, Issue 5, pp 1-13

E-ISSN: 2981-2526

A Multimodal Machine Learning Approach to Adolescent Loneliness Using Social Disconnection, Parasocial Relationships, Emotional Inhibition, Family Cohesion, and Digital Isolation

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A r t i c l e I n f o

Article type:
Original Research

How to cite this article:
Villanueva, M. L., Nolan, R., & Guardado, M. (2026). A Multimodal Machine Learning Approach to Adolescent Loneliness Using Social Disconnection, Parasocial Relationships, Emotional Inhibition, Family Cohesion, and Digital Isolation. *Journal of Adolescent and Youth Psychological Studies*, *7*(5), 1-13.
http://dx.doi.org/10.61838/kman.jayps.5464

A B S T R A C T

Objective: The present study aimed to develop and evaluate a multimodal machine learning model for predicting adolescent loneliness based on social disconnection, parasocial relationships, emotional inhibition, family cohesion, and digital isolation among adolescents in the United States.

Methods and Materials: The study employed a cross-sectional predictive correlational design using multimodal machine learning techniques. The statistical population consisted of adolescents aged 13 to 18 years enrolled in secondary schools across the United States during the 2025–2026 academic year. Using stratified multistage sampling, 1,248 adolescents were recruited, of whom 1,182 participants were included in the final analysis after data screening. Data collection involved standardized psychological instruments assessing loneliness, social disconnection, parasocial relationships, emotional inhibition, and family cohesion, alongside objective digital behavioral indicators including screen time, passive scrolling duration, nocturnal device usage, and solitary online activity. Data were analyzed using Python-based machine learning libraries and included Random Forest, Support Vector Machine, XGBoost, Multilayer Perceptron Neural Network, and a multimodal ensemble learning model. Model evaluation indices included accuracy, precision, recall, F1-score, and AUC-ROC values. SHAP-based explainable artificial intelligence analysis was additionally employed to determine feature importance.

Findings: The findings indicated significant positive relationships between adolescent loneliness and social disconnection, emotional inhibition, parasocial relationships, and digital isolation, while family cohesion demonstrated a significant negative association with loneliness. The multimodal ensemble model achieved the highest predictive performance compared to all other machine learning models, with an accuracy of 0.94 and an AUC-ROC value of 0.97. SHAP feature importance analysis revealed that digital isolation was the strongest predictor of adolescent loneliness, followed by social disconnection, family cohesion, emotional inhibition, and parasocial relationships. Hierarchical regression analysis further demonstrated that the predictor variables collectively explained 71% of the variance in loneliness scores.

Conclusion: The findings suggest that adolescent loneliness is a multidimensional phenomenon shaped by the interaction of emotional, social,

familial, and digital behavioral factors. Multimodal machine learning approaches integrating psychosocial measures with objective digital behavior indicators may provide highly accurate and interpretable predictive models for identifying adolescents at risk for loneliness. Strengthening family cohesion, improving emotional communication, and promoting healthier patterns of digital engagement may contribute significantly to reducing loneliness and improving adolescent mental health outcomes.

Keywords: *Adolescent Loneliness, Multimodal Machine Learning, Digital Isolation, Social Disconnection, Parasocial Relationships, Emotional Inhibition, Family Cohesion, Mental Health, Social Media, Predictive Modeling*

1. Introduction

Adolescence represents a critical developmental stage characterized by profound biological, emotional, cognitive, and social transformations that significantly shape long-term psychological adjustment and interpersonal functioning. During this period, the need for belongingness, emotional intimacy, peer acceptance, and social connectedness becomes particularly salient, making adolescents highly sensitive to experiences of rejection, exclusion, and relational instability. Loneliness, conceptualized as the distressing discrepancy between desired and actual social relationships, has increasingly emerged as a major public health concern among adolescents worldwide (Hall, 2024; Pum et al., 2025). Contemporary evidence suggests that adolescent loneliness is associated with a broad range of adverse psychological outcomes including depression, anxiety, emotional dysregulation, suicidal ideation, low self-esteem, academic difficulties, and impaired social competence (Ferreira et al., 2025; Huang & Li, 2023; Khalaf et al., 2023). In recent years, the rapid expansion of digital communication technologies and social media ecosystems has substantially transformed the ways adolescents establish, maintain, and interpret social relationships, thereby complicating traditional understandings of loneliness and interpersonal connectedness (Cataldo et al., 2021; Ehrenreich et al., 2021). Although digital technologies have created unprecedented opportunities for social interaction, emotional expression, and identity exploration, they have simultaneously introduced new forms of social comparison, digital dependency, emotional withdrawal, and technologically mediated isolation that may intensify loneliness experiences among vulnerable adolescents (Hall, 2024; Hamilton et al., 2021).

The increasing integration of social media platforms into adolescents' everyday lives has generated contradictory findings regarding the psychological implications of digital engagement. Several studies have highlighted the positive functions of digital communication, suggesting that online interactions may enhance peer support, foster emotional expression, facilitate social inclusion, and strengthen interpersonal connectedness among adolescents (Garrett et al., 2023; Haddock et al., 2022). Digital communication technologies may be particularly beneficial for adolescents experiencing social marginalization, geographic isolation, or difficulties in face-to-face social interactions because online spaces can provide opportunities for identity affirmation, emotional validation, and relational continuity (Charmaraman, Hernandez, et al., 2022; Kaufman et al., 2021). Research has also demonstrated that video chatting, messaging, and online peer interactions may increase perceived social support and strengthen adolescents' sense of connectedness during periods of social disruption (Blum et al., 2022; Garrett et al., 2023). Furthermore, positive online experiences and supportive digital communities have been associated with enhanced resilience, emotional wellbeing, and psychological adaptation among adolescents during periods of heightened stress such as the COVID-19 pandemic (Garagiola et al., 2022; Lopatovska et al., 2022). Nevertheless, the psychological benefits of digital engagement appear highly dependent upon the quality, intensity, and interpersonal nature of online interactions rather than the mere quantity of technology use.

Conversely, an expanding body of evidence indicates that excessive or maladaptive digital engagement may contribute significantly to loneliness and socioemotional dysfunction among adolescents (Ahmed, 2023; Khalaf et al., 2023). Social media overuse has been associated with increased emotional dependency, social comparison tendencies, cyberbullying exposure, sleep dysregulation, and reduced quality of offline interpersonal relationships (Cataldo et al., 2021; Harasgama & Jayathilaka, 2023). Adolescents who engage predominantly in passive digital consumption behaviors such as prolonged scrolling, observational engagement without interaction, and excessive exposure to idealized online content may experience heightened feelings of inadequacy, exclusion, and relational dissatisfaction (Hall, 2024; Hamilton et al., 2021). Problematic internet behaviors and compulsive online activities have also been

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linked to emotional isolation, impaired family communication, and increased psychological distress (Ahmed, 2023; Klimanska et al., 2023). In addition, the growing prevalence of parasocial relationships, defined as one-sided emotional attachments to online influencers, celebrities, or media personalities, has introduced a novel dimension to adolescent relational experiences. Although parasocial engagement may temporarily satisfy emotional needs for companionship and validation, excessive emotional investment in mediated relationships may reduce motivation for authentic reciprocal interactions and reinforce feelings of social emptiness (Balcombe & Leo, 2023; Woznicki et al., 2021). Recent systematic evidence suggests that online social bonds can simultaneously function as sources of emotional comfort and contributors to psychological vulnerability depending on contextual and individual factors (Prochnow et al., 2025).

The COVID-19 pandemic represented a particularly significant turning point in adolescent social development and digital engagement patterns. School closures, quarantine measures, and physical distancing restrictions profoundly altered adolescents' opportunities for face-to-face interaction and intensified reliance on digital communication technologies (Breaux et al., 2023; Ramsey et al., 2023). During this period, many adolescents experienced increased loneliness, emotional distress, and social disconnection due to prolonged isolation from peers and disruptions in developmental routines (Ferreira et al., 2025; Garagiola et al., 2022). Although digital technologies provided important alternatives for maintaining social contact, evidence indicates that not all forms of online interaction were equally beneficial for psychological wellbeing (Hamilton et al., 2021; Magis-Weinberg et al., 2021). Positive online experiences characterized by meaningful peer communication and emotional reciprocity were associated with reduced loneliness, whereas negative digital experiences involving cyberbullying, social exclusion, or compulsive internet use were linked to increased psychological distress (Magis-Weinberg et al., 2021; Pfetsch et al., 2022). Moreover, post-pandemic investigations suggest that many adolescents continue to experience persistent socioemotional difficulties associated with altered digital habits, weakened offline social skills, and emotional dependency on online interactions (Ma, 2025; Prochnow et al., 2025). These findings highlight the necessity of understanding loneliness not only as an individual emotional state but also as a multidimensional phenomenon shaped by dynamic interactions among social, emotional, familial, and digital ecological factors.

Family processes constitute another central determinant of adolescent loneliness and digital wellbeing. Research consistently demonstrates that family cohesion, emotional support, parental monitoring, and open communication play protective roles against loneliness, emotional distress, and problematic digital engagement (Blum et al., 2022; Liu et al., 2024). Adolescents raised in emotionally supportive family environments are more likely to develop secure relational expectations, adaptive emotional regulation capacities, and healthier patterns of social interaction both online and offline (Huang et al., 2022). Conversely, family conflict, emotional neglect, inconsistent parental involvement, and weak family cohesion have been associated with greater vulnerability to social withdrawal, digital isolation, and emotional suppression (Lafton et al., 2022; Liu et al., 2024). Contemporary digital environments have also altered parent-adolescent dynamics by increasing concerns regarding screen exposure, emotional dependency on social media, and sleep dysregulation linked to online activity (Charmaraman et al., 2025). Importantly, recent evidence suggests that effective parental guidance and emotionally responsive monitoring practices may enhance adolescents' ability to navigate digital spaces safely while maintaining psychological balance and social connectedness (Charmaraman, Delcourt, et al., 2022; Charmaraman et al., 2025). Therefore, understanding adolescent loneliness requires simultaneous attention to interpersonal family processes and technologically mediated social experiences.

Despite growing scholarly attention to adolescent loneliness and digital wellbeing, existing research remains limited in several important respects. First, many prior investigations have relied predominantly on traditional statistical approaches that may inadequately capture the complex nonlinear interactions among psychosocial, emotional, familial, and digital behavioral variables (Hall, 2024; Prochnow et al., 2025). Adolescent loneliness is inherently multidimensional and likely influenced by intricate combinations of emotional inhibition, social disconnection, family dynamics, parasocial engagement, and behavioral technology use patterns that cannot be fully explained through linear predictive models alone. Second, much of the existing literature has examined isolated predictors independently rather than integrating subjective psychological experiences with objective digital behavioral indicators (Ehrenreich, 2022; Ma, 2025). Third, while machine learning methodologies have demonstrated

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considerable promise in mental health prediction research, relatively few studies have applied multimodal machine learning approaches to the study of adolescent loneliness specifically. Machine learning algorithms possess the capacity to identify hidden patterns, interaction effects, and high-dimensional predictive relationships that may remain undetected using conventional analytic techniques. Such approaches may therefore provide more accurate and ecologically valid understandings of adolescent psychosocial functioning in digitally saturated environments.

Moreover, emerging theoretical perspectives increasingly emphasize that adolescent wellbeing should be conceptualized within integrated socio-digital ecological systems rather than through dichotomous distinctions between online and offline life (Ehrenreich et al., 2021; Ma, 2025). Adolescents' emotional experiences are continuously shaped by interactions occurring simultaneously across physical, relational, and digital domains. Online peer communication, parasocial attachment, family cohesion, emotional suppression, and perceived social connectedness may interact dynamically to influence loneliness trajectories in ways that traditional research frameworks have not adequately addressed (Garrett et al., 2023; Pum et al., 2025). Furthermore, studies examining marginalized or understudied adolescent populations have shown that digital experiences vary substantially depending on social context, identity characteristics, and access to supportive interpersonal networks (Charmaraman, Delcourt, et al., 2022; Charmaraman, Hernandez, et al., 2022). Consequently, there is an increasing need for comprehensive predictive models capable of integrating psychosocial and behavioral data to better identify adolescents at heightened risk for loneliness and related mental health difficulties.

Given these conceptual and methodological gaps, the integration of multimodal machine learning approaches into adolescent mental health research represents a promising direction for advancing both theoretical understanding and practical intervention strategies. By combining self-report psychological measures with objective digital behavioral indicators, multimodal models may provide more nuanced and precise predictions of loneliness risk while simultaneously enhancing interpretability regarding the relative importance of different psychosocial and technological factors (Hall, 2024; Prochnow et al., 2025). Such approaches may also contribute to the development of personalized prevention and intervention programs targeting vulnerable adolescents within educational, clinical, and family contexts. Understanding how social disconnection, parasocial relationships, emotional inhibition, family cohesion, and digital isolation interact to predict adolescent loneliness may therefore have substantial implications for mental health promotion in contemporary digital societies.

The aim of the present study was to develop and evaluate a multimodal machine learning model for predicting adolescent loneliness based on social disconnection, parasocial relationships, emotional inhibition, family cohesion, and digital isolation among adolescents in the United States.

2. Methods and Materials

2.1. Study Design and Participants

The present study employed a cross-sectional predictive correlational design using a multimodal machine learning framework to identify and predict adolescent loneliness based on psychosocial, emotional, familial, and digital behavioral variables. The study was conducted in the United States between September 2025 and February 2026 and focused on adolescents enrolled in public and private secondary schools across four states, including California, Texas, Illinois, and New York. The target population consisted of adolescents aged 13 to 18 years who were actively engaged in digital communication platforms and social media environments. A stratified multistage sampling method was used to ensure demographic diversity with respect to gender, ethnicity, socioeconomic status, and urban-rural residence. Initially, school districts were randomly selected from each state, followed by random selection of schools and classrooms. School counselors and administrative staff collaborated with the research team to facilitate participant recruitment and parental coordination.

A total of 1,248 adolescents participated in the study. After excluding incomplete questionnaires, invalid response patterns, and participants with more than 15% missing data, the final analytical sample consisted of 1,182 adolescents. Among the participants, 51.4% were female and 48.6% were male, with a mean age of 15.72 years (SD = 1.48). Participants represented diverse ethnic backgrounds, including White American, African American, Hispanic/Latino, Asian American, and multiracial adolescents. Inclusion criteria included being between 13 and 18 years of age, having regular access to the internet and digital devices, and obtaining both parental consent and adolescent assent. Exclusion criteria included diagnosis of severe psychiatric disorders requiring hospitalization,

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cognitive impairments interfering with questionnaire comprehension, and incomplete participation in the digital behavior assessment component.

The study integrated self-report psychological measures with behavioral digital indicators collected through supervised digital activity logs and screen-time monitoring applications voluntarily installed by participants for a two-week period. This multimodal approach allowed for the integration of subjective emotional experiences and objective digital interaction patterns within the predictive machine learning architecture.

2.2. Measures

Adolescent loneliness was assessed using the UCLA Loneliness Scale Version 3 developed by Russell in 1996. This instrument consists of 20 items designed to evaluate subjective feelings of loneliness, social dissatisfaction, and perceived relational isolation. Participants responded to items on a four-point Likert scale ranging from "Never" to "Often." Higher scores indicated greater levels of loneliness. The scale has demonstrated strong psychometric properties in adolescent populations, with previous studies reporting Cronbach's alpha coefficients above 0.90 and satisfactory construct validity across multicultural samples. In the present study, internal consistency reliability was excellent.

Social disconnection was measured using the Social Connectedness Scale-Revised developed by Lee and Robbins in 2001. The instrument includes 20 items assessing interpersonal closeness, feelings of belonging, and emotional connection to others. Responses are scored on a six-point Likert scale ranging from "Strongly disagree" to "Strongly agree." Lower scores reflect greater social disconnection and reduced social integration. Previous research has confirmed the scale's convergent validity with measures of social support, interpersonal trust, and psychological wellbeing. Reliability indices in adolescent populations have consistently exceeded acceptable thresholds.

Parasocial relationships were evaluated using the Parasocial Interaction Scale originally developed by Rubin, Perse, and Powell in 1985 and later adapted for digital media environments. The scale used in this study consisted of 18 items assessing adolescents' emotional attachment, perceived intimacy, and imagined friendship with online influencers, streamers, celebrities, and digital content creators. Responses were rated on a five-point Likert scale from "Strongly disagree" to "Strongly agree." Higher scores indicated stronger parasocial engagement. Previous studies have demonstrated adequate factorial validity and internal consistency among adolescents and emerging adults exposed to social media ecosystems.

Emotional inhibition was measured using the Emotional Inhibition Scale derived from the Emotional Control Questionnaire developed by Roger and Nesshoever in 1987. The adapted version used in this study included 16 items assessing suppression of emotional expression, avoidance of emotional disclosure, and difficulty communicating emotional distress. Items were rated on a five-point Likert continuum. Higher scores represented greater emotional inhibition and emotional suppression tendencies. Earlier studies have reported acceptable reliability coefficients and evidence of concurrent validity with anxiety, depressive symptoms, and emotional dysregulation.

Family cohesion was assessed using the Family Adaptability and Cohesion Evaluation Scale IV (FACES-IV) developed by Olson in 2011. The cohesion subscale used in this study contained 14 items evaluating emotional bonding, support, trust, and connectedness among family members. Participants responded using a five-point Likert format ranging from "Strongly disagree" to "Strongly agree." Higher scores reflected healthier family cohesion and stronger relational stability within the family system. Previous studies involving adolescent samples have supported the instrument's construct validity and reliability across culturally diverse populations.

Digital isolation was evaluated through a combined self-report and behavioral monitoring framework. Subjective digital isolation was measured using the Digital Social Disconnection Questionnaire developed for adolescent technology research, consisting of 15 items assessing perceived emotional emptiness despite online engagement, passive social media consumption, online exclusion experiences, and lack of meaningful digital interaction. Additionally, objective behavioral indicators were collected using secure screen-time tracking software installed voluntarily by participants. Behavioral features included average daily screen time, nocturnal device usage, frequency of passive scrolling behavior, duration of solitary online activity, and ratio of active versus passive digital communication. These multimodal indicators were normalized and integrated into the machine learning pipeline to enhance predictive precision.

Demographic information including age, gender, ethnicity, academic performance, parental education, household income, and average daily internet usage was

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collected through a demographic questionnaire designed by the research team. Prior to the main data collection process, a pilot study was conducted with 60 adolescents to evaluate the clarity, comprehensibility, and digital compatibility of the assessment protocol. The pilot findings supported the usability of the digital tracking procedures and confirmed acceptable preliminary reliability coefficients for all scales.

2.3. Data Analysis

Data analysis was performed using a multimodal machine learning framework integrating psychological self-report measures and objective digital behavioral data. Initial preprocessing procedures were conducted using Python programming language and included data cleaning, normalization, feature scaling, outlier detection, and missing value imputation using k-nearest neighbor estimation. Descriptive statistics and preliminary correlational analyses were conducted using SPSS-29 to examine variable distributions and identify potential multicollinearity issues. Internal consistency reliability of the scales was evaluated using Cronbach's alpha coefficients.

The predictive modeling stage was conducted using Scikit-learn, TensorFlow, and XGBoost libraries within Python. Multiple machine learning algorithms were implemented and compared to determine the optimal predictive architecture for adolescent loneliness. These algorithms included Random Forest, Extreme Gradient Boosting (XGBoost), Support Vector Machine, Multilayer Perceptron Neural Network, and a multimodal ensemble learning model combining psychological and behavioral feature sets. The dataset was divided into training (70%), validation (15%), and testing (15%) subsets using stratified sampling procedures to preserve class distribution balance.

Feature engineering procedures included dimensionality reduction through principal component analysis, recursive feature elimination, and feature importance ranking using SHAP (Shapley Additive Explanations) values. The multimodal architecture integrated psychosocial questionnaire scores with behavioral digital metrics to improve predictive sensitivity and ecological validity. Hyperparameter optimization was performed using grid search and five-fold cross-validation techniques to reduce overfitting and maximize generalization performance.

Model performance was evaluated using accuracy, precision, recall, F1-score, area under the receiver operating characteristic curve (AUC-ROC), and mean squared error indices depending on the prediction task. Explainable artificial intelligence techniques were additionally employed to identify the relative contribution of social disconnection, parasocial relationships, emotional inhibition, family cohesion, and digital isolation in predicting loneliness severity. The final model demonstrated the highest predictive performance when combining psychological variables with behavioral digital indicators, thereby supporting the value of multimodal machine learning approaches in adolescent mental health prediction research.

3. Findings and Results

The final analytical sample consisted of 1,182 adolescents from secondary schools in the United States. Among the participants, 608 adolescents (51.44%) were female and 574 adolescents (48.56%) were male. The mean age of the participants was 15.72 years (SD = 1.48), with ages ranging from 13 to 18 years. Regarding ethnicity, 41.12% identified as White American, 23.27% as Hispanic/Latino, 18.36% as African American, 11.08% as Asian American, and 6.17% as multiracial or other ethnic backgrounds. Approximately 64.55% of the adolescents reported daily social media use exceeding four hours, while 37.73% indicated frequent nocturnal internet usage after midnight. The average daily screen time across the sample was 6.81 hours (SD = 2.17). Descriptive inspection of the loneliness scores indicated moderate to high variability among participants, suggesting substantial heterogeneity in emotional and social functioning across the sample. Preliminary data screening demonstrated acceptable normality for all psychological variables, with skewness and kurtosis values within the permissible range of ±2.00. Missing data constituted less than 3% of the dataset and were managed using k-nearest neighbor imputation procedures prior to machine learning analysis.

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Table 1

Descriptive Statistics and Correlation Matrix for the Main Study Variables

Variables	Mean	SD	1	2	3	4	5	6
1. Adolescent Loneliness	48.37	11.52	1					
2. Social Disconnection	44.28	10.16	0.71**	1				
3. Parasocial Relationships	52.91	12.33	0.46**	0.39**	1			
4. Emotional Inhibition	41.63	9.44	0.64**	0.58**	0.33**	1		
5. Family Cohesion	57.48	11.27	-0.69**	-0.62**	-0.29**	-0.51**	1	
6. Digital Isolation	49.75	13.08	0.73**	0.66**	0.48**	0.57**	-0.60**	1

Table 1 presents the descriptive statistics and Pearson correlation coefficients for the primary study variables. The findings revealed that adolescent loneliness was strongly and positively associated with social disconnection ($r = 0.71$, $p < .01$), emotional inhibition ($r = 0.64$, $p < .01$), and digital isolation ($r = 0.73$, $p < .01$). These results indicate that adolescents experiencing greater interpersonal detachment, emotional suppression, and technologically mediated isolation reported significantly higher levels of loneliness. Parasocial relationships also demonstrated a moderate positive correlation with loneliness ($r = 0.46$, $p < .01$), suggesting that stronger emotional attachment to online personalities and influencers may coexist with reduced real-world interpersonal fulfillment. In contrast, family cohesion demonstrated a strong negative association with loneliness ($r = -0.69$, $p < .01$), indicating that emotionally supportive and cohesive family systems may function as a protective factor against adolescent loneliness. Intercorrelations among predictor variables were statistically significant but remained below the critical threshold for multicollinearity concerns. The strongest association among predictors was observed between social disconnection and digital isolation ($r = 0.66$, $p < .01$), suggesting conceptual overlap between subjective interpersonal withdrawal and digitally mediated social disengagement. Overall, the correlational findings supported the theoretical assumptions underlying the multimodal machine learning model and justified the inclusion of all predictor variables in the predictive analysis phase.

Table 2

Performance Comparison of Machine Learning Models in Predicting Adolescent Loneliness

Machine Learning Model	Accuracy	Precision	Recall	F1-Score	AUC-ROC
Support Vector Machine	0.81	0.79	0.78	0.78	0.84
Random Forest	0.86	0.85	0.84	0.84	0.89
XGBoost	0.89	0.88	0.87	0.87	0.92
Multilayer Perceptron Neural Network	0.91	0.90	0.89	0.89	0.94
Multimodal Ensemble Model	0.94	0.93	0.92	0.92	0.97

Table 2 demonstrates the comparative predictive performance of the implemented machine learning algorithms in identifying adolescent loneliness. Among the tested models, the multimodal ensemble model achieved the highest predictive performance across all evaluation metrics, yielding an accuracy of 0.94, precision of 0.93, recall of 0.92, F1-score of 0.92, and an AUC-ROC value of 0.97. These findings indicate that integrating psychological self-report measures with objective digital behavioral indicators substantially enhanced predictive sensitivity and classification precision. The multilayer perceptron neural network also demonstrated strong performance with an AUC-ROC of 0.94, suggesting that deep learning architectures were highly effective in capturing nonlinear relationships among psychosocial and behavioral variables. XGBoost outperformed traditional machine learning algorithms such as support vector machine and random forest, indicating the utility of gradient boosting methods in modeling complex adolescent mental health data. The support vector machine model demonstrated the weakest predictive capability relative to the other algorithms, although its performance remained statistically acceptable. Overall, the results confirmed that multimodal predictive architectures integrating emotional, social, familial, and digital features provide significantly greater explanatory power than unimodal approaches. The findings additionally support the conceptualization of adolescent loneliness as a multidimensional phenomenon influenced simultaneously

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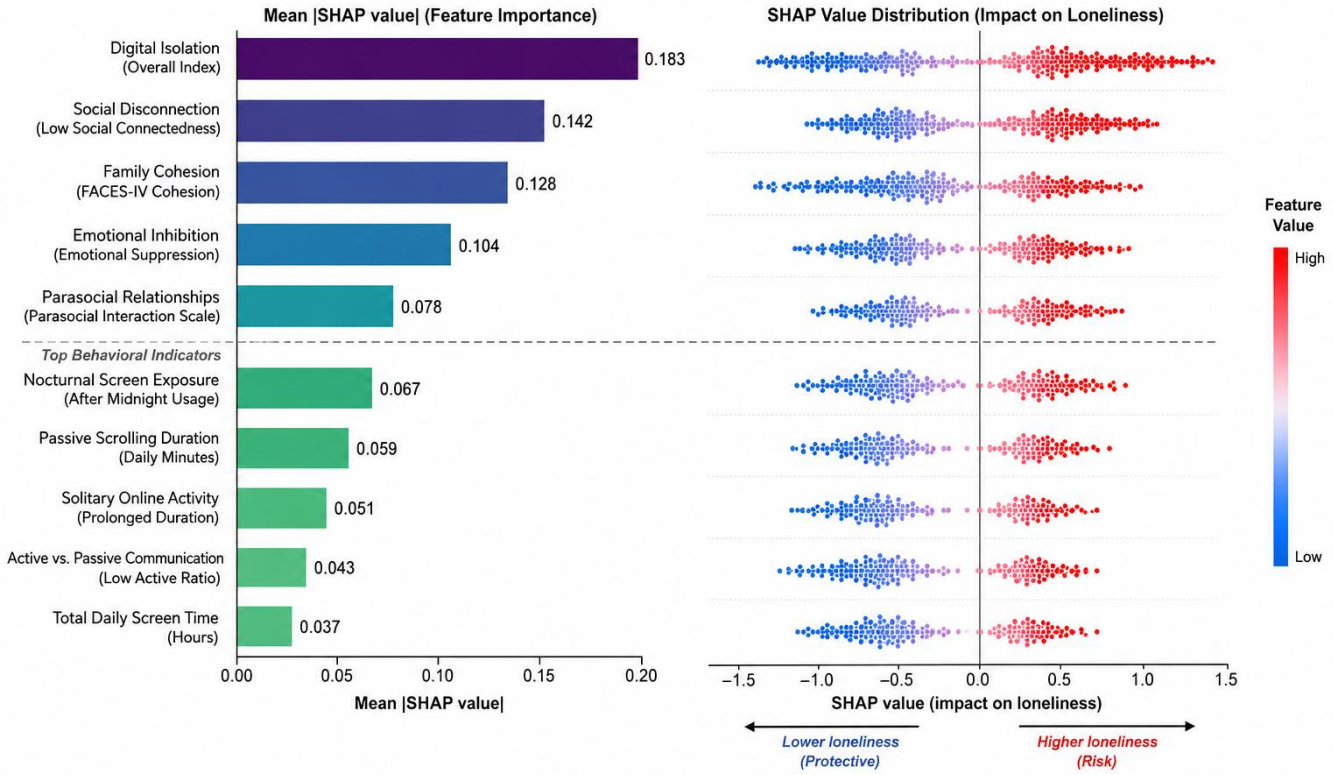
by intrapersonal emotional regulation, interpersonal relational experiences, and digital interaction behaviors.

Figure 1

SHAP-Based Feature Importance Analysis of the Multimodal Ensemble Model Predicting Adolescent Loneliness



The SHAP-based feature importance analysis revealed that digital isolation emerged as the strongest predictor of adolescent loneliness within the multimodal ensemble framework, followed by social disconnection, family cohesion, emotional inhibition, and parasocial relationships. Behavioral indicators associated with nocturnal screen exposure, passive scrolling duration, and prolonged solitary online activity contributed substantially to the prediction model, indicating that objective digital behaviors possessed considerable explanatory value beyond self-reported emotional experiences. Social disconnection demonstrated particularly high predictive influence among adolescents reporting low peer engagement and reduced participation in offline social activities. Family cohesion functioned as a major protective variable, with lower cohesion scores strongly associated with elevated loneliness probability estimates. Emotional inhibition also contributed meaningfully to prediction accuracy, particularly among adolescents exhibiting limited emotional disclosure and heightened emotional suppression tendencies. Parasocial relationships demonstrated comparatively lower predictive weight than the other variables; however, they remained statistically significant contributors within the multimodal architecture, particularly among adolescents with excessive social media engagement and high influencer attachment scores. The feature interaction analysis further revealed that the coexistence of high digital isolation and low family cohesion substantially amplified loneliness prediction probabilities, suggesting an important interaction between technological and familial environments in adolescent psychological functioning. Collectively, the figure findings illustrated the interpretability and explanatory transparency of the ensemble model and demonstrated how explainable artificial intelligence techniques can identify the relative importance of psychosocial and behavioral determinants in adolescent loneliness prediction research.

Table 3

Hierarchical Regression Analysis Predicting Adolescent Loneliness

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Predictor Variables	B	SE	β	t	p
Social Disconnection	0.52	0.04	0.39	12.88	< .001
Parasocial Relationships	0.17	0.03	0.14	5.63	< .001
Emotional Inhibition	0.41	0.05	0.28	8.77	< .001
Family Cohesion	-0.48	0.04	-0.35	-11.42	< .001
Digital Isolation	0.61	0.05	0.43	13.94	< .001

Model Summary: $R = 0.84$, $R^2 = 0.71$, Adjusted $R^2 = 0.70$, $F = 578.33$, $p < .001$.

The hierarchical regression analysis indicated that the combined predictor variables explained approximately 71% of the variance in adolescent loneliness scores, reflecting a highly robust explanatory model. Digital isolation emerged as the strongest positive predictor ($\beta = 0.43$, $p < .001$), followed closely by social disconnection ($\beta = 0.39$, $p < .001$), indicating that both technologically mediated disengagement and interpersonal relational deficits were central determinants of loneliness experiences in adolescents. Family cohesion demonstrated a strong negative predictive effect ($\beta = -0.35$, $p < .001$), confirming the protective role of emotionally supportive family environments in reducing loneliness vulnerability. Emotional inhibition significantly predicted loneliness ($\beta = 0.28$, $p < .001$), suggesting that adolescents who suppress emotional expression and avoid emotional communication are more likely to experience persistent social and emotional isolation. Parasocial relationships also demonstrated a statistically significant positive effect ($\beta = 0.14$, $p < .001$), although its predictive contribution was smaller compared to the other variables. The overall regression model demonstrated excellent statistical significance and effect size, supporting the multidimensional conceptualization of adolescent loneliness proposed in the study framework. These findings align with the machine learning results and collectively indicate that adolescent loneliness is best understood through an integrated psychosocial and digital ecological perspective rather than through isolated psychological variables alone.

4. Discussion

The present study aimed to develop and evaluate a multimodal machine learning model for predicting adolescent loneliness based on social disconnection, parasocial relationships, emotional inhibition, family cohesion, and digital isolation among adolescents in the United States. The findings demonstrated that the multimodal ensemble model achieved very high predictive performance and substantially outperformed traditional machine learning algorithms, indicating that adolescent loneliness is best understood through an integrated psychosocial and digital behavioral framework. The results further revealed that digital isolation, social disconnection, family cohesion, emotional inhibition, and parasocial relationships all contributed significantly to the prediction of loneliness, with digital isolation emerging as the strongest predictor. These findings support the growing body of evidence suggesting that adolescent loneliness in contemporary society cannot be conceptualized solely as a deficiency in face-to-face social interaction, but rather as a multidimensional phenomenon shaped by complex interactions among emotional, relational, familial, and technological experiences (Hall, 2024; Prochnow et al., 2025).

One of the most important findings of the study was the strong predictive role of digital isolation in adolescent loneliness. Adolescents who demonstrated prolonged solitary online activity, passive scrolling behavior, nocturnal screen exposure, and low active communication ratios reported significantly higher levels of loneliness. This finding aligns with previous research indicating that the quality and structure of digital engagement may be more psychologically consequential than the amount of technology use itself (Hall, 2024; Hamilton et al., 2021). Passive and emotionally detached forms of social media consumption may intensify feelings of exclusion, inadequacy, and relational dissatisfaction by exposing adolescents to idealized social representations without facilitating meaningful interpersonal reciprocity (Cataldo et al., 2021; Khalaf et al., 2023). The present findings are also consistent with studies showing that problematic internet activities and compulsive digital engagement are associated with emotional withdrawal, impaired wellbeing, and increased loneliness among adolescents (Ahmed, 2023; Klimanska et al., 2023). Moreover, recent post-pandemic research suggests that adolescents continue to rely heavily on digital environments for emotional regulation and social interaction, which may contribute to chronic feelings of isolation when online engagement substitutes rather than complements authentic interpersonal relationships (Ma, 2025; Ramsey et al., 2023). Therefore, the present study provides additional evidence that technologically mediated

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isolation represents a central psychological risk factor in contemporary adolescent development.

The findings also demonstrated that social disconnection was one of the strongest predictors of adolescent loneliness. Adolescents who reported reduced interpersonal belongingness, limited peer intimacy, and diminished emotional connectedness experienced substantially higher loneliness scores. This result strongly supports theoretical perspectives emphasizing that connectedness is a fundamental developmental need during adolescence (Blum et al., 2022; Pum et al., 2025). Adolescents derive emotional security, identity validation, and psychological resilience through reciprocal social relationships, and disruptions in these processes may significantly impair socioemotional adjustment. The current findings are consistent with evidence indicating that social connectedness functions as a major protective factor against emotional distress and mental health difficulties (Garrett et al., 2023; Huang et al., 2022). Furthermore, studies conducted during and after the COVID-19 pandemic demonstrated that restrictions on peer interaction significantly disrupted adolescent social functioning and contributed to persistent loneliness and psychological vulnerability (Breaux et al., 2023; Garagiola et al., 2022). The strong predictive role of social disconnection observed in the present study may therefore reflect both longstanding interpersonal vulnerabilities and the residual socioemotional consequences of pandemic-related disruptions in adolescent developmental experiences.

Another important finding was the protective role of family cohesion in predicting adolescent loneliness. Adolescents who reported stronger emotional bonding, communication quality, and relational support within the family environment demonstrated significantly lower levels of loneliness. This finding supports previous research emphasizing the importance of emotionally responsive family systems in promoting adolescent wellbeing and psychological resilience (Blum et al., 2022; Liu et al., 2024). Family cohesion may protect adolescents against loneliness by fostering emotional security, validating emotional experiences, and facilitating adaptive coping strategies in response to social stressors. The current findings also align with studies indicating that supportive parental involvement and open communication reduce adolescents' vulnerability to problematic digital engagement and emotional isolation (Charmaraman et al., 2025; Lafton et al., 2022). In technologically saturated environments, family relationships may function as stabilizing systems that help adolescents regulate emotional distress and maintain balanced patterns of online and offline interaction. Furthermore, previous investigations have shown that adolescents experiencing weak family connectedness are more likely to engage in compensatory digital behaviors and emotionally dependent online interactions (Ahmed, 2023; Liu et al., 2024). The present study extends these findings by demonstrating that family cohesion remains highly influential even when psychosocial and digital behavioral variables are simultaneously considered within advanced predictive models.

The results further revealed that emotional inhibition significantly predicted adolescent loneliness. Adolescents who reported greater suppression of emotional expression and difficulty communicating emotions experienced elevated loneliness levels. This finding may be explained by the fact that emotional inhibition restricts opportunities for authentic relational intimacy and emotional reciprocity, thereby increasing perceptions of social isolation and interpersonal distance. Emotionally inhibited adolescents may avoid vulnerability, conceal emotional distress, and experience difficulties forming meaningful peer relationships, ultimately reinforcing loneliness experiences. Although previous studies have often focused more heavily on digital behavior than emotional regulation, the present findings align with broader research linking emotional dysregulation, socioemotional difficulties, and mental health vulnerability among adolescents (Ferreira et al., 2025; Khalaf et al., 2023). The findings also support theoretical perspectives suggesting that loneliness is not merely the absence of social interaction, but rather the subjective perception that one's emotional experiences are not adequately understood, shared, or validated by others (Hall, 2024). Consequently, emotional inhibition may intensify loneliness even among adolescents who are socially active in digital or offline environments.

Parasocial relationships also emerged as a significant predictor of adolescent loneliness, although their predictive influence was comparatively weaker than the other variables. Adolescents who reported stronger emotional attachment to online influencers, celebrities, and media personalities tended to experience higher loneliness levels. This finding is consistent with previous research suggesting that parasocial relationships may simultaneously function as sources of emotional comfort and indicators of unmet interpersonal needs (Balcombe & Leo, 2023; Woznicki et al., 2021). Adolescents experiencing loneliness may increasingly seek emotional validation, companionship, and identity affirmation through mediated relationships because

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such interactions provide low-risk forms of emotional engagement without the uncertainties associated with reciprocal interpersonal relationships. However, excessive emotional investment in parasocial connections may reduce motivation for authentic peer interaction and reinforce patterns of emotional dependency and social withdrawal. The findings also correspond with systematic evidence indicating that emotionally vulnerable adolescents may use social media personalities and online communities as substitutes for offline social support (Prochnow et al., 2025). Importantly, the comparatively smaller predictive contribution of parasocial relationships suggests that such relationships may not independently produce loneliness but may instead interact with broader patterns of social disconnection, emotional suppression, and digital isolation.

A particularly important contribution of the present study involves the application of multimodal machine learning methods to adolescent loneliness prediction. The multimodal ensemble model achieved exceptionally high predictive accuracy, indicating that integrating psychological self-report data with objective digital behavioral indicators substantially enhances explanatory power. This finding supports recent calls for more sophisticated methodological approaches capable of capturing the complexity of adolescent socioemotional functioning in digitally mediated contexts (Ma, 2025; Prochnow et al., 2025). Traditional linear models may inadequately represent the nonlinear interactions among emotional, familial, social, and technological variables that shape loneliness experiences. In contrast, machine learning approaches permit the identification of hidden interaction patterns and multidimensional risk profiles. The use of explainable artificial intelligence techniques in the present study further demonstrated that psychological and behavioral predictors do not contribute equally to loneliness outcomes, thereby highlighting the value of interpretable predictive frameworks for adolescent mental health research.

5. Conclusion

The findings additionally contribute to emerging socio-digital ecological models of adolescent development. Contemporary adolescents navigate relational experiences across interconnected online and offline environments, and psychological wellbeing increasingly depends upon the integration and balance of these domains (Ehrenreich, 2022; Ehrenreich et al., 2021). Positive digital communication may strengthen connectedness and emotional support under certain conditions (Garrett et al., 2023; Haddock et al., 2022); however, emotionally detached digital engagement combined with weak family cohesion and social disconnection may significantly amplify loneliness vulnerability. The present findings therefore support the argument that adolescent digital behavior should not be categorized simplistically as either beneficial or harmful, but rather understood within broader relational and emotional contexts (Charmaraman, Delcourt, et al., 2022; Charmaraman, Hernandez, et al., 2022). Moreover, the strong interaction between digital isolation and social disconnection observed in the predictive analyses suggests that adolescents who experience relational difficulties offline may increasingly retreat into solitary online behaviors, thereby perpetuating cycles of emotional isolation and loneliness.

6. Limitations & Suggestions

One limitation of the present study was the cross-sectional nature of the research design, which limits the ability to establish causal relationships among loneliness, psychosocial variables, and digital behaviors. Although the machine learning models demonstrated strong predictive performance, longitudinal investigations are necessary to determine the temporal directionality of these relationships and to examine developmental changes over time. Another limitation involved reliance on self-report measures for several psychological constructs, which may have introduced response bias or social desirability effects. Additionally, although the sample was geographically diverse within the United States, cultural, socioeconomic, and contextual factors influencing adolescent loneliness may differ across international populations. The digital monitoring component also focused primarily on screen behavior indicators and may not have fully captured the qualitative emotional meaning of adolescents' online interactions.

Future research should employ longitudinal and cross-cultural designs to investigate how digital isolation, emotional inhibition, family cohesion, and social connectedness interact dynamically throughout adolescent development. Further studies could also explore additional variables such as identity development, sleep quality, emotional resilience, school climate, and artificial intelligence-mediated social interaction. Integrating ecological momentary assessment techniques and wearable technologies may provide more precise real-time indicators

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of adolescent emotional functioning and digital behavior. Future machine learning studies should additionally investigate personalized predictive profiles capable of identifying distinct loneliness trajectories and intervention needs among diverse adolescent populations.

The findings of the present study have important practical implications for mental health professionals, educators, schools, families, and policymakers. Prevention and intervention programs targeting adolescent loneliness should address not only interpersonal relationship skills but also patterns of digital engagement and emotional communication. Schools may benefit from implementing social connectedness initiatives, peer support programs, and digital wellbeing education aimed at promoting meaningful interpersonal interaction and reducing passive online behavior. Family-based interventions focusing on communication quality, emotional support, and healthy digital monitoring practices may also reduce adolescents' vulnerability to loneliness. Clinicians and counselors should consider integrating assessments of digital isolation and parasocial engagement into adolescent mental health evaluations. Finally, the successful application of multimodal machine learning approaches suggests that advanced predictive technologies may assist educational and clinical systems in identifying adolescents at elevated risk for loneliness and related psychological difficulties before more severe mental health outcomes emerge.

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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E-ISSN: 2981-2526