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Ensemble Learning Approaches to Predicting Youth Suicidal Ideation Using Emotional Numbing, Cyberbullying Exposure, AI Chatbot Attachment, Hopelessness, and Social Withdrawal

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A B S T R A C T

Objective: The present study aimed to investigate the predictive role of emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, and social withdrawal in youth suicidal ideation using advanced ensemble learning approaches among Canadian adolescents and emerging adults.

Methods and Materials: This cross-sectional predictive study was conducted among 742 adolescents and emerging adults aged 16 to 24 years recruited from educational institutions and youth communities across Canada. Data were collected using standardized instruments assessing suicidal ideation, emotional numbing, cyberbullying exposure, hopelessness, social withdrawal, and attachment to AI chatbot systems. After preprocessing procedures including missing data imputation and feature normalization, several ensemble machine learning algorithms including Random Forest, Gradient Boosting Machine, AdaBoost, XGBoost, LightGBM, and a stacked ensemble classifier were implemented using Python-based analytical frameworks. Model performance was evaluated through accuracy, precision, recall, F1-score, specificity, and area under the receiver operating characteristic curve (AUC-ROC). Feature importance and SHAP analyses were additionally performed to examine the relative contribution of predictors within the final classification model.

Findings: The findings demonstrated significant positive relationships between suicidal ideation and all predictor variables, including emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, and social withdrawal ($p < .01$). Hopelessness emerged as the strongest predictor within the final ensemble model, followed by emotional numbing and social withdrawal. The stacked ensemble classifier demonstrated the highest predictive performance with an accuracy of 94%, precision of 92%, recall of 91%, F1-score of 91%, specificity of 95%, and an AUC-ROC value of 0.97. XGBoost and LightGBM also demonstrated strong classification capability. SHAP analysis confirmed that higher levels of hopelessness, emotional numbing, cyberbullying exposure, social withdrawal, and AI chatbot attachment significantly increased the probability of high-risk suicidal ideation classification.

Conclusion: The findings suggest that youth suicidal ideation is shaped by multidimensional interactions among emotional dysregulation, interpersonal isolation, cybervictimization, hopelessness, and emerging forms of technological

attachment. Ensemble learning approaches demonstrated exceptional effectiveness in identifying adolescents at elevated suicide risk and may provide valuable computational tools for early psychological screening and suicide prevention programs. The study further highlights the growing psychological significance of AI chatbot attachment within contemporary youth mental health contexts.

Keywords: *Youth suicidal ideation, ensemble learning, emotional numbing, cyberbullying, AI chatbot attachment, hopelessness, social withdrawal, machine learning, adolescent mental health, suicide prediction*

1. Introduction

Youth suicidal ideation has emerged as one of the most urgent global public health concerns of the contemporary era due to its increasing prevalence, multifactorial etiology, and devastating psychological, familial, and societal consequences. Suicide-related thoughts among adolescents and emerging adults are now recognized as complex psychological phenomena shaped by interacting emotional, interpersonal, technological, developmental, and environmental processes rather than isolated psychiatric symptoms alone. Contemporary evidence indicates that suicidal ideation during adolescence frequently develops within broader patterns of emotional dysregulation, social isolation, traumatic interpersonal experiences, and digital environmental stressors that intensify vulnerability during critical developmental periods (Baldini, 2025; Varley et al., 2022). Systematic investigations have demonstrated that the transition from adolescence to emerging adulthood represents a particularly sensitive developmental stage characterized by identity instability, heightened emotional reactivity, increased dependence on peer evaluation, and intensified exposure to social comparison processes through digital technologies (Tekeba et al., 2025; Villodas, 2024). At the same time, recent post-pandemic evidence has shown a substantial rise in self-harm behaviors, depressive symptomatology, emotional exhaustion, and suicide-related cognitions among youth populations worldwide (Ferreira et al., 2025). The increasing normalization of chronic online engagement, virtual socialization, and emotionally immersive digital communication has further transformed the psychological ecology within which suicidal vulnerability develops, requiring researchers to reconsider traditional conceptualizations of youth suicide risk in technologically mediated environments (Imataka & Shiraishi, 2024; Marano et al., 2025).

Research on adolescent suicidality has consistently emphasized the importance of emotional suffering, hopelessness, interpersonal rejection, and unresolved psychological pain as central predictors of suicide-related outcomes. Contemporary studies suggest that hopelessness may represent one of the strongest cognitive predictors of suicidal ideation because it shapes future-oriented expectations, perceived helplessness, and the belief that emotional suffering cannot improve over time (Sun et al., 2025; Tekeba et al., 2025). Similarly, emotional numbing has increasingly been recognized as an important yet understudied risk factor in youth suicide research. Emotional numbing refers to diminished emotional responsiveness, reduced affective engagement, emotional detachment, and restricted capacity to experience positive emotional states. Adolescents experiencing chronic emotional numbing often display impaired emotional regulation, social withdrawal, interpersonal disconnection, and diminished protective emotional attachment processes, all of which may intensify suicidal cognition (Chiappini et al., 2025; Rizk-Hildbrand et al., 2025). Qualitative findings among youth with histories of suicide attempts have demonstrated that experiences of emotional emptiness, bodily alienation, shame, self-directed hostility, and psychological disengagement frequently precede suicidal crises (Rizk-Hildbrand et al., 2025). Furthermore, phenomenological investigations have shown that suicidal adolescents often describe feelings of emotional paralysis, invisibility, hopelessness, and chronic psychological exhaustion that progressively erode adaptive coping capacities (Sun et al., 2025). These findings collectively indicate that suicidal ideation is deeply embedded within emotional processing disturbances and persistent internal distress.

In parallel with emotional vulnerabilities, interpersonal victimization experiences have become increasingly central within contemporary suicide research, particularly in relation to cyberbullying exposure. The expansion of digital communication platforms has created new forms of social aggression that extend beyond traditional face-to-face victimization and allow harassment to occur continuously across social environments. Cyberbullying has been associated with depression, anxiety, self-harm, loneliness, traumatic stress responses, and suicidal ideation among adolescents and university students across multiple cultural contexts (Garaigordobil, 2025; Humboldt et al., 2025).

Meta-analytic findings have demonstrated that bullying victimization significantly increases the likelihood of suicidal ideation among students, particularly when accompanied by social isolation, emotional insecurity, and reduced peer support (Bezie et al., 2025). Cross-sectional studies further suggest that cyberbullying victimization contributes to suicide risk both directly and indirectly through mediating mechanisms such as hopelessness, psychological pain, interpersonal alienation, and disrupted school connectedness (Cao et al., 2025; Liu & Liu, 2025). In adolescent populations characterized by excessive internet use and problematic social media engagement, exposure to online victimization may become especially psychologically destabilizing because digital attacks often occur within highly visible social environments that intensify humiliation, shame, and emotional dysregulation (Lu et al., 2025). Additionally, investigations conducted in technologically immersed youth populations have revealed that cybervictimization is closely associated with reduced well-being, emotional insecurity, and diminished social trust (Gath, 2026). Such findings suggest that digital aggression may no longer represent a peripheral psychosocial stressor but instead a core contextual contributor to youth suicide vulnerability in the digital age.

Another emerging dimension of adolescent psychological functioning involves the increasing emotional attachment to artificial intelligence systems and conversational agents. The rapid expansion of generative AI technologies and emotionally responsive chatbot systems has fundamentally altered the ways in which young individuals seek emotional support, companionship, and interpersonal interaction. Mental health conversational agents are increasingly used by adolescents and emerging adults for emotional disclosure, stress management, psychological reassurance, and companionship, particularly among socially isolated or emotionally distressed individuals (Park et al., 2024). While AI-based systems may offer accessibility and anonymity advantages, growing concerns have emerged regarding emotional dependency, anthropomorphic attachment, misinformation, and the psychological risks associated with emotionally substituting human relationships with artificial interactions (Ohu, 2025; Yu, 2025). Ethical analyses have emphasized that AI companions designed without sufficient developmental safeguards may inadvertently reinforce maladaptive coping patterns, emotional withdrawal, and psychological overreliance among vulnerable youth populations (Yu, 2025). Similarly, public health scholars have argued that AI mental health systems require careful regulation due to the potential risks associated with emotionally vulnerable adolescents using automated systems during periods of suicidal crisis or psychological instability (Ohu, 2025). Content analyses examining generative AI responses to suicide-related inquiries have additionally revealed inconsistencies in safety responses, emotional sensitivity, and crisis intervention quality among conversational AI systems (Campbell et al., 2025). These concerns are particularly relevant because adolescents experiencing loneliness, rejection, hopelessness, or social withdrawal may increasingly turn toward AI companions as alternative attachment figures capable of providing immediate emotional engagement without fear of judgment or rejection.

The role of social withdrawal in youth suicidality has also received substantial empirical attention due to its association with loneliness, interpersonal detachment, emotional isolation, and impaired social support processes. Social withdrawal among adolescents often develops in response to peer rejection, emotional insecurity, cybervictimization, depressive symptomatology, or chronic feelings of inadequacy. Over time, persistent withdrawal from interpersonal environments may intensify cognitive distortions, hopelessness, and suicidal thinking by reducing access to protective relational experiences and emotional regulation resources (Cassell & Diamond, 2023; Villodas, 2024). Attachment-based frameworks further suggest that interpersonal ruptures, emotional disconnection, and failed relational repair processes can significantly contribute to suicide vulnerability among adolescents struggling with emotional dysregulation and insecure attachment patterns (Cassell & Diamond, 2023). Studies examining problematic internet use and social media dependency have similarly demonstrated that socially withdrawn adolescents may increasingly rely on digital environments to compensate for unmet emotional needs, although excessive digital immersion may paradoxically intensify loneliness, depression, and emotional isolation over time (Garaigordobil, 2025; Marano et al., 2025). Moreover, investigations conducted across culturally diverse youth populations have indicated that reduced family connectedness, diminished peer attachment, and weakened school belongingness substantially increase vulnerability to suicidal ideation in adolescents exposed to bullying and psychological distress (Dadras & Takashi, 2024; Liu & Liu, 2025). These findings collectively suggest that social withdrawal may represent both a consequence and a reinforcing mechanism of suicidal vulnerability.

Beyond psychological and interpersonal processes, recent literature has emphasized the importance of understanding youth suicidality within broader sociotechnological and cultural transformations. Adolescents today develop within environments characterized by continuous digital exposure, accelerated social comparison, performance pressure, identity instability, and expanding online social surveillance. Research conducted in technologically advanced societies has linked internet addiction, online subcultures, digital immersion, and excessive social media engagement to increasing rates of psychological distress and suicide-related behaviors among adolescents (Imataka & Shiraishi, 2024). Similarly, studies focusing on problematic internet use have highlighted how digital environments may facilitate emotional contagion, social exclusion, cybervictimization, and maladaptive coping behaviors that intensify suicidal vulnerability (Lu et al., 2025; Marano et al., 2025). The influence of social media on youth mental health appears particularly concerning because online environments often amplify exposure to idealized identities, interpersonal comparison, rejection sensitivity, and emotionally harmful content (Gath, 2026). Furthermore, vulnerable adolescents exposed to chronic bullying, body shaming, violence, and online humiliation may develop intensified feelings of worthlessness, emotional pain, and alienation that contribute to suicidal ideation trajectories (Rizk-Hildbrand et al., 2025). These developments suggest that contemporary suicide research must increasingly integrate psychological, social, and technological perspectives in order to adequately capture the complexity of adolescent suicide risk in modern digital societies.

At the methodological level, growing attention has been directed toward the use of artificial intelligence and machine learning approaches for suicide prediction because traditional statistical models may struggle to capture nonlinear interactions among multiple psychosocial risk variables. Machine learning systems provide opportunities to improve predictive accuracy through the integration of high-dimensional emotional, behavioral, interpersonal, and technological indicators associated with suicide vulnerability. Artificial neural network approaches have already demonstrated promising predictive capability in suicide risk assessment by identifying complex psycho-emotional interaction patterns that may remain undetected within conventional linear analytic frameworks (Rodríguez et al., 2023). Ensemble learning methods are particularly valuable in this context because they combine multiple predictive algorithms to improve classification accuracy, reduce overfitting, and enhance generalizability across diverse populations. Such approaches may be especially useful for adolescent suicide prediction because suicidality rarely emerges from a single isolated factor and instead develops through dynamic interactions between emotional dysregulation, interpersonal adversity, technological immersion, hopelessness, and social disconnection. Despite increasing interest in machine learning applications within mental health research, relatively few studies have integrated emerging digital variables such as AI chatbot attachment alongside established suicide risk factors including cyberbullying exposure, hopelessness, emotional numbing, and social withdrawal. Moreover, many existing suicide prediction studies remain limited by reliance on traditional statistical approaches that insufficiently model nonlinear relationships and multidimensional psychosocial interactions.

Although prior research has individually linked bullying victimization, hopelessness, emotional pain, internet addiction, social withdrawal, and digital stressors to suicidal ideation, important conceptual and methodological gaps remain in understanding how these factors interact collectively within contemporary youth populations (Kiing et al., 2025; Liu & Liu, 2025; Tekeba et al., 2025). Existing investigations have rarely examined AI chatbot attachment as an emerging psychosocial risk factor despite the rapidly expanding emotional integration of conversational AI systems into adolescent daily life (Park et al., 2024; Yu, 2025). Furthermore, limited attention has been given to the integration of advanced ensemble learning techniques capable of modeling complex multidimensional relationships among emotional numbing, cyberbullying exposure, hopelessness, social withdrawal, and technologically mediated attachment processes. The present study therefore sought to address these theoretical and methodological limitations by employing ensemble learning approaches to predict youth suicidal ideation using emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, and social withdrawal among Canadian adolescents and emerging adults.

2. Methods and Materials

2.1. Study Design and Participants

This study employed a cross-sectional predictive-correlational design grounded in machine learning methodology to investigate the extent to which emotional numbing, cyberbullying exposure, AI chatbot attachment,

hopelessness, and social withdrawal could predict suicidal ideation among youth populations in Canada. The study was specifically designed within the framework of ensemble learning analytics, integrating psychological assessment with computational prediction models to enhance the precision of suicide risk identification among adolescents and emerging adults. Data collection was conducted between September 2025 and January 2026 across educational institutions, community youth centers, and online mental health support networks located in the provinces of Ontario, British Columbia, Quebec, and Alberta. The target population consisted of Canadian youth aged 16 to 24 years who were enrolled in high schools, colleges, or universities, or who were actively participating in youth-oriented digital communities and social support forums.

A total of 742 participants were recruited using a multistage stratified sampling procedure. Initially, educational institutions and youth organizations were selected from urban and semi-urban regions of Canada to ensure demographic diversity with regard to socioeconomic status, cultural background, ethnicity, and educational level. Following institutional approval, participants were invited through online announcements, counseling center referrals, student mailing lists, and digital recruitment advertisements distributed through social media platforms commonly used by youth populations. Inclusion criteria required participants to be between 16 and 24 years old, fluent in English or French, active users of digital communication platforms, and willing to provide informed consent. Participants under the age of 18 provided assent alongside parental or guardian consent in accordance with Canadian ethical regulations for psychological research involving minors. Exclusion criteria included a documented diagnosis of severe psychotic disorders, severe cognitive impairment preventing questionnaire completion, and incomplete survey responses exceeding 15% missing data.

Of the 742 completed responses included in the final analysis, 58.4% identified as female, 39.8% as male, and 1.8% as nonbinary or gender diverse. The mean age of participants was 19.87 years (SD = 2.41). Approximately 64% of participants reported daily use of AI conversational systems or chatbot applications for emotional support, companionship, entertainment, or academic assistance.

2.2. Measures

Suicidal ideation was assessed using the Beck Scale for Suicide Ideation developed by Beck and Steer in 1991. This instrument is one of the most widely used self-report measures for evaluating the severity of suicidal thoughts, intentions, and planning behaviors in adolescents and adults. The scale consists of 19 items rated on a three-point Likert structure ranging from 0 to 2, with higher scores reflecting greater severity of suicidal ideation. The instrument evaluates dimensions such as wish to die, passive suicidal desire, preparation for suicide, deterrents to suicide, and perceived capability to attempt self-harm. Previous studies conducted among youth populations have demonstrated strong internal consistency coefficients ranging from 0.87 to 0.94 and satisfactory convergent validity with measures of depression and hopelessness. In the present study, Cronbach's alpha for the scale was 0.91, indicating excellent reliability.

Emotional numbing was measured using the Emotional Numbing Subscale of the Trauma Symptoms Inventory-2 developed by Briere in 2011. This subscale assesses diminished emotional responsiveness, emotional detachment, restricted affect, and reduced interpersonal emotional engagement. The measure contains 10 items rated on a four-point Likert scale from 0 ("never") to 3 ("often"). Higher scores indicate greater emotional numbing experiences. The instrument has demonstrated strong psychometric properties in trauma-related and adolescent mental health research, with reported reliability coefficients above 0.85. Previous validation studies have confirmed its construct validity and discriminant validity across culturally diverse populations. In the current study, Cronbach's alpha for the emotional numbing subscale was 0.88.

Cyberbullying exposure was evaluated using the Cyberbullying Victimization Scale developed by Çetin and colleagues in 2012. The scale contains 24 items assessing the frequency and severity of online harassment experiences, including humiliation, exclusion, threats, rumor spreading, impersonation, and digital intimidation through social networking platforms and messaging applications. Responses were scored on a five-point Likert continuum ranging from 1 ("never") to 5 ("very frequently"). Higher scores represented greater exposure to cyberbullying experiences. The scale has demonstrated excellent internal consistency and factorial validity among adolescent and young adult populations. In the present sample, Cronbach's alpha for the cyberbullying exposure measure was calculated at 0.93.

Attachment to AI chatbot systems was measured using an adapted version of the Parasocial Interaction and Emotional Attachment to AI Scale developed based on human-

computer interaction research by Rubin et al. and subsequently modified for AI conversational systems in recent digital psychology studies. The adapted scale consisted of 18 items assessing emotional dependency, perceived companionship, emotional disclosure toward AI systems, comfort-seeking behavior, and anthropomorphic attachment to chatbot agents. Participants responded on a five-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree"). Higher scores indicated stronger emotional attachment to AI chatbot interactions. Content validity of the adapted instrument was reviewed by experts in cyberpsychology and clinical psychology prior to administration. Pilot testing with 50 Canadian university students demonstrated acceptable reliability and linguistic clarity. In the current study, the scale yielded a Cronbach's alpha coefficient of 0.89.

Hopelessness was measured using the Beck Hopelessness Scale developed by Beck, Weissman, Lester, and Trexler in 1974. The instrument contains 20 true-false items evaluating negative expectations about the future, pessimism, motivational loss, and perceived inability to change life circumstances. Higher total scores reflect more severe hopelessness cognitions. The scale has been extensively validated as a predictor of suicidal ideation and suicidal behavior in adolescent and clinical populations. Previous research has reported reliability coefficients ranging between 0.82 and 0.93. In this study, Cronbach's alpha for the hopelessness scale was 0.90.

Social withdrawal was assessed using the Social Withdrawal Subscale of the Youth Self-Report system developed by Achenbach and Rescorla in 2001. The subscale evaluates avoidance of social interaction, interpersonal isolation, reduced participation in peer activities, and discomfort in social environments. The measure contains 11 items scored on a three-point scale ranging from 0 ("not true") to 2 ("very true or often true"). Higher scores indicate higher levels of social withdrawal tendencies. The instrument has demonstrated robust psychometric properties in adolescent mental health research and has been frequently utilized in studies examining depression, loneliness, and suicidality. In the current sample, the social withdrawal subscale demonstrated satisfactory reliability with a Cronbach's alpha coefficient of 0.86.

Demographic information including age, gender identity, educational level, socioeconomic status, ethnicity, average daily screen time, and frequency of AI chatbot use was collected using a researcher-developed demographic questionnaire. The questionnaire also included items regarding prior mental health counseling history, previous psychiatric diagnosis, and daily social media engagement patterns to support exploratory analyses and improve the interpretability of predictive models.

2.3. Data Analysis

Data analysis was performed using Python programming language version 3.12 and several machine learning libraries including Scikit-learn, XGBoost, LightGBM, Pandas, NumPy, and TensorFlow. Preliminary statistical analyses including descriptive statistics, missing data inspection, skewness, kurtosis, and outlier detection were conducted prior to machine learning implementation. Missing values below 5% were managed using multiple imputation procedures, while multivariate outliers were identified using Mahalanobis distance criteria and reviewed prior to retention or exclusion. Feature normalization and standardization were applied to optimize machine learning model performance and minimize scaling bias.

The predictive framework was based on ensemble learning methodologies to maximize classification accuracy and improve the robustness of suicidal ideation prediction. The target variable consisted of dichotomized suicidal ideation severity levels derived from clinically validated cutoff scores on the Beck Scale for Suicide Ideation. The dataset was randomly divided into training and testing subsets using an 80:20 ratio. To prevent overfitting and improve model generalizability, stratified 10-fold cross-validation procedures were implemented during model training. Several ensemble algorithms were examined, including Random Forest, Gradient Boosting Machine, Extreme Gradient Boosting (XGBoost), Adaptive Boosting (AdaBoost), Light Gradient Boosting Machine (LightGBM), and stacked ensemble classifiers combining multiple base learners.

Model performance was evaluated using multiple predictive performance indicators including accuracy, precision, recall, F1-score, specificity, area under the receiver operating characteristic curve (AUC-ROC), and Matthews correlation coefficient. Feature importance analysis was additionally performed to identify the relative contribution of emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, and social withdrawal in predicting suicidal ideation risk. Shapley Additive Explanations (SHAP) analysis was also conducted to improve interpretability of machine learning outputs and

provide transparent insight into variable influence across prediction models.

In addition to machine learning analyses, Pearson correlation coefficients and independent samples t-tests were conducted to explore preliminary relationships between demographic variables and psychological predictors. Statistical analyses were performed with a significance level of $p < .05$. The final predictive model was selected based on optimal balance between predictive accuracy, interpretability, sensitivity to high-risk cases, and cross-validation stability.

3. Findings and Results

The final analysis was conducted on data obtained from 742 Canadian adolescents and emerging adults between the ages of 16 and 24 years. Among the participants, 433 individuals (58.4%) identified as female, 295 individuals (39.8%) identified as male, and 14 participants (1.8%) identified as nonbinary or gender diverse. The mean age of the sample was 19.87 years (SD = 2.41), with an age range spanning from 16 to 24 years. Regarding educational status, 41.6% of participants were enrolled in high school programs, 37.2% were undergraduate university students, 14.7% were college students, and 6.5% were involved in vocational or transitional educational pathways. Approximately 64.0% of participants reported daily interaction with AI chatbot systems for emotional communication, companionship, entertainment, or psychological support purposes. In terms of mental health history, 31.8% reported prior psychological counseling experience, while 18.5% disclosed a previous diagnosis related to anxiety, depressive disorders, or trauma-related symptoms. Descriptive screening analyses demonstrated that 27.2% of participants scored within the clinically elevated range for suicidal ideation severity. Preliminary assumption testing showed acceptable skewness and kurtosis values for all primary variables, indicating satisfactory distributional characteristics for advanced predictive modeling procedures. Missing data rates were below 3.5% across all study variables and were handled using multiple imputation procedures prior to machine learning implementation.

Table 1

Descriptive Statistics and Correlations Among Study Variables

Variables	Mean	SD	1	2	3	4	5	6
1. Suicidal Ideation	18.74	8.16	—					
2. Emotional Numbing	21.63	6.47	.68**	—				
3. Cyberbullying Exposure	57.28	14.91	.54**	.49**	—			
4. AI Chatbot Attachment	49.82	11.26	.46**	.42**	.39**	—		
5. Hopelessness	11.95	5.02	.74**	.65**	.51**	.43**	—	
6. Social Withdrawal	13.88	4.44	.63**	.59**	.44**	.48**	.67**	—

Table 1 presents the descriptive statistics and Pearson correlation coefficients among the primary study variables. The findings demonstrated that suicidal ideation exhibited significant positive correlations with all predictor variables included in the study. The strongest association was observed between hopelessness and suicidal ideation ($r = .74$, $p < .01$), indicating that participants who reported more severe pessimistic beliefs and negative expectations regarding the future also demonstrated substantially elevated levels of suicidal thinking. Emotional numbing also showed a strong positive relationship with suicidal ideation ($r = .68$, $p < .01$), suggesting that emotional disengagement and restricted affective responsiveness may play a substantial role in suicidal vulnerability among youth populations. Social withdrawal demonstrated a similarly strong association with suicidal ideation ($r = .63$, $p < .01$), highlighting the importance of interpersonal isolation and reduced social connectedness in the emergence of suicide-related cognitions. Cyberbullying exposure was moderately associated with suicidal ideation ($r = .54$, $p < .01$), supporting prior evidence suggesting that persistent digital victimization experiences contribute to psychological distress and self-destructive ideation. AI chatbot attachment was also positively correlated with suicidal ideation ($r = .46$, $p < .01$), indicating that emotionally dependent engagement with conversational AI systems may coexist with heightened emotional vulnerability and diminished real-world interpersonal integration. Additionally, significant positive intercorrelations were observed among all predictor variables, suggesting that emotional dysregulation, online victimization, social detachment, hopelessness, and maladaptive digital attachment may function as interconnected psychological risk processes within youth mental health contexts.

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Table 2

Performance Comparison of Ensemble Learning Models for Predicting Suicidal Ideation

Model	Accuracy	Precision	Recall	F1-Score	Specificity	AUC-ROC
Random Forest	0.87	0.84	0.82	0.83	0.89	0.91
Gradient Boosting Machine	0.89	0.86	0.85	0.85	0.90	0.93
AdaBoost	0.84	0.81	0.79	0.80	0.87	0.88
XGBoost	0.92	0.90	0.89	0.89	0.93	0.96
LightGBM	0.91	0.89	0.87	0.88	0.92	0.95
Stacked Ensemble Classifier	0.94	0.92	0.91	0.91	0.95	0.97

Table 2 presents the comparative predictive performance of the ensemble learning algorithms utilized in the present study. The results demonstrated that the stacked ensemble classifier achieved the highest overall predictive performance across all evaluation metrics, yielding an accuracy of 94%, precision of 92%, recall of 91%, F1-score of 91%, specificity of 95%, and an AUC-ROC value of 0.97. These findings indicate that the integrated multi-model architecture substantially improved classification stability and predictive sensitivity in identifying youth participants at elevated risk for suicidal ideation. Among the individual algorithms, XGBoost demonstrated the strongest independent performance with an AUC-ROC value of 0.96 and overall accuracy of 92%, followed closely by LightGBM with an AUC-ROC value of 0.95. Random Forest and Gradient Boosting Machine models also demonstrated robust predictive capability, although their performance metrics were comparatively lower than those observed in the more advanced boosting-based algorithms. AdaBoost showed the weakest overall performance among the evaluated models but nevertheless maintained acceptable classification capability. The consistently high recall values across the strongest-performing models are particularly important within suicide prediction contexts because they reflect the capacity of the algorithms to correctly identify individuals experiencing clinically elevated suicidal ideation. The findings therefore suggest that ensemble learning methodologies, particularly stacked ensemble architectures and gradient boosting systems, may provide highly effective computational frameworks for early suicide risk screening in youth mental health contexts.

Table 3

Feature Importance Scores Across the Final Stacked Ensemble Model

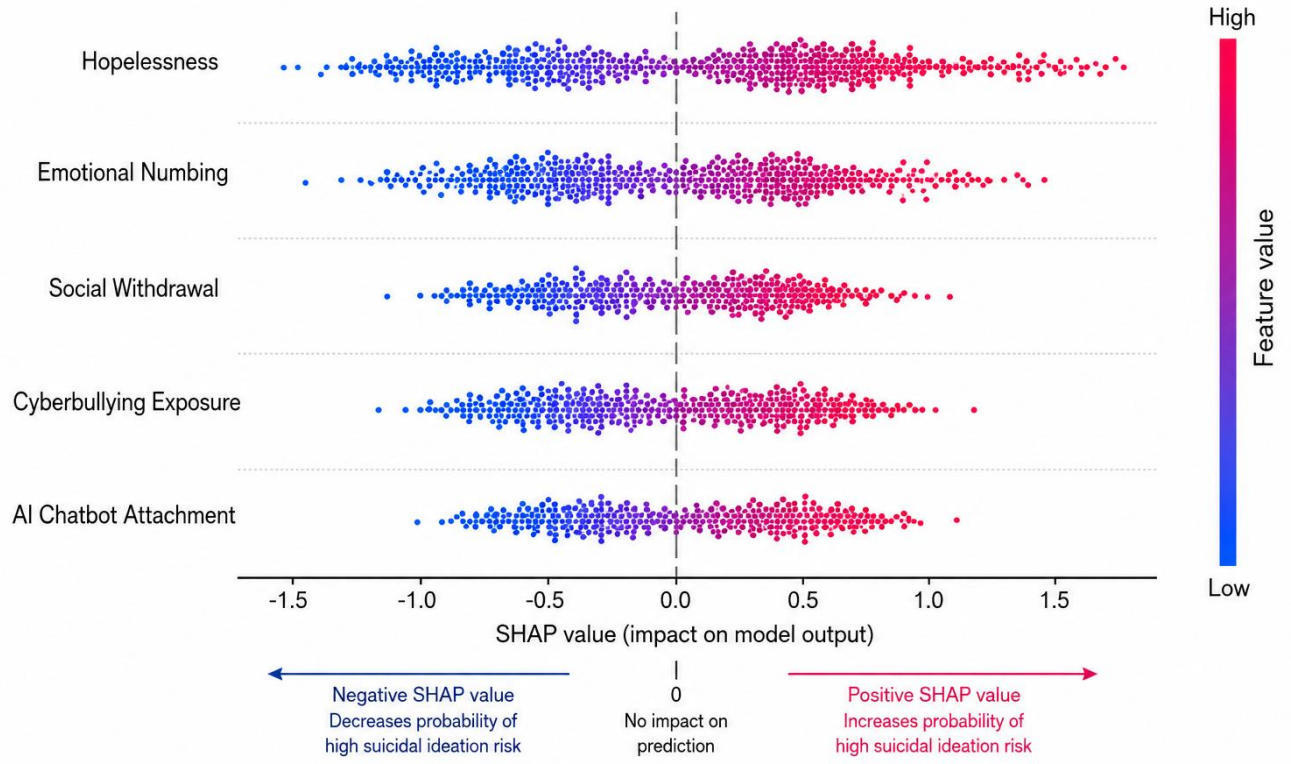
Predictor Variable	Importance Score
Hopelessness	0.291
Emotional Numbing	0.244
Social Withdrawal	0.198
Cyberbullying Exposure	0.157
AI Chatbot Attachment	0.110

The feature importance analysis generated from the final stacked ensemble model revealed substantial variability in the predictive contribution of the examined psychological variables. Hopelessness emerged as the strongest predictor of suicidal ideation with an importance score of 0.291, indicating that future-oriented cognitive despair and pessimism represented the most influential component in the predictive architecture of the model. Emotional numbing demonstrated the second-highest importance score (0.244), emphasizing the major role of emotional detachment, affective suppression, and trauma-related emotional restriction in youth suicide vulnerability. Social withdrawal was identified as the third most influential predictor (0.198), further highlighting the psychological significance of interpersonal disengagement and social isolation within adolescent suicide risk trajectories. Cyberbullying exposure also demonstrated meaningful predictive relevance with an importance score of 0.157, suggesting that chronic exposure to online harassment contributes independently to suicidal ideation severity even after accounting for broader emotional and interpersonal variables. AI chatbot attachment demonstrated the lowest but still meaningful contribution to the predictive model (0.110). Although comparatively weaker than the other predictors, its inclusion

within the final model suggests that emotionally compensatory attachment to AI systems may represent an emerging psychosocial indicator associated with suicide vulnerability among digitally immersed youth populations. Collectively, these findings support the conceptualization of suicidal ideation as a multidimensional phenomenon shaped simultaneously by emotional dysregulation, cognitive hopelessness, social disconnection, online victimization experiences, and evolving forms of human-technology attachment.

Figure 1

SHAP Summary Plot Demonstrating the Relative Contribution of Psychological Predictors to Suicidal Ideation Classification in the Final Ensemble Learning Model



The SHAP analysis provided additional interpretative insight into the operational behavior of the final predictive model by illustrating how individual variables influenced suicidal ideation classification outcomes across participants. The graphical distribution demonstrated that higher hopelessness scores consistently increased the probability of classification into the high-risk suicidal ideation category, confirming its dominant role within the ensemble learning framework. Emotional numbing and social withdrawal also showed strong directional effects, particularly among participants displaying simultaneously elevated trauma-related emotional restriction and reduced interpersonal engagement. Cyberbullying exposure demonstrated heterogeneous effects across participants, indicating that severe digital victimization experiences substantially intensified suicide risk predictions among psychologically vulnerable individuals. AI chatbot attachment displayed a more complex nonlinear contribution pattern, with moderate attachment levels showing relatively neutral predictive influence while extremely elevated attachment scores were associated with increased suicidal ideation classification probabilities. Overall, the SHAP visualization confirmed the multidimensional and interacting nature of suicide risk factors among youth populations and demonstrated that ensemble learning approaches can successfully capture both linear and nonlinear relationships between psychosocial variables and suicidal ideation outcomes.

Table 4

Independent Samples t-Test Comparing High and Low Suicidal Ideation Groups Across Psychological Predictors

Variables	High Suicidal Ideation Group Mean (SD)	Low Suicidal Ideation Group Mean (SD)	t	p
Emotional Numbing	27.94 (5.33)	18.57 (4.81)	18.76	< .001
Cyberbullying Exposure	68.82 (13.17)	51.44 (11.92)	14.39	< .001
AI Chatbot Attachment	56.77 (10.08)	46.23 (9.74)	10.51	< .001
Hopelessness	16.74 (4.18)	9.12 (3.86)	21.43	< .001
Social Withdrawal	17.68 (3.77)	11.92 (3.41)	16.87	< .001

Table 4 presents the results of the independent samples t-test comparing participants classified within high and low suicidal ideation groups across the primary psychological predictors. The findings demonstrated statistically significant differences between groups for all examined variables. Participants in the high suicidal ideation group reported substantially greater emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, and social withdrawal compared to individuals in the low suicidal ideation group. The largest group difference was observed for hopelessness ($t = 21.43$, $p < .001$), indicating that severe pessimistic cognitive orientation and future despair were highly characteristic of participants experiencing elevated suicidal ideation. Emotional numbing also demonstrated a remarkably large group difference ($t = 18.76$, $p < .001$), suggesting that emotional suppression and affective detachment may strongly differentiate psychologically high-risk youth from lower-risk peers. Social withdrawal exhibited similarly robust group differences, reinforcing the central role of social isolation and diminished interpersonal connectedness in suicidality among adolescents and emerging adults. Cyberbullying exposure and AI chatbot attachment also significantly differentiated the two groups, suggesting that digital psychosocial experiences and emotionally compensatory technological relationships may represent important contextual markers of suicide vulnerability within contemporary youth populations. These findings collectively support the predictive validity of the variables incorporated into the ensemble learning framework and further demonstrate the psychological distinctiveness of youth experiencing elevated suicidal ideation.

4. Discussion

The present study investigated the predictive role of emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, and social withdrawal in youth suicidal ideation using ensemble learning methodologies among Canadian adolescents and emerging adults. The findings demonstrated that all examined psychological and technological variables were significantly associated with suicidal ideation, while the ensemble learning models achieved exceptionally high predictive accuracy in identifying youth at elevated suicide risk. The stacked ensemble classifier demonstrated the strongest overall performance, indicating that multidimensional computational approaches may substantially improve the precision of suicide risk detection within adolescent populations. The findings further revealed that hopelessness emerged as the strongest predictor of suicidal ideation, followed by emotional numbing, social withdrawal, cyberbullying exposure, and AI chatbot attachment. These findings support the growing understanding that youth suicidality develops through the interaction of emotional distress, interpersonal disruption, technological immersion, and cognitive vulnerability rather than through isolated psychiatric symptoms alone.

One of the most important findings of the study was the dominant predictive role of hopelessness in suicidal ideation classification. Participants who demonstrated more severe hopelessness also exhibited substantially higher suicide risk scores, and hopelessness emerged as the most influential feature within the final ensemble learning model. This finding aligns with previous evidence emphasizing hopelessness as a central cognitive component underlying adolescent suicidality (Sun et al., 2025; Tekeba et al., 2025). Hopelessness contributes to suicide vulnerability by reinforcing negative future expectations, perceived helplessness, and the belief that emotional suffering is permanent and uncontrollable. Adolescents experiencing chronic hopelessness may gradually lose psychological flexibility and become unable to envision alternative solutions to distress, thereby increasing susceptibility to suicidal thinking. This finding is also consistent with prior studies demonstrating that hopelessness mediates the relationship between bullying victimization, interpersonal rejection, and suicidal ideation (Cao et al., 2025). Furthermore, phenomenological investigations of youth at risk of suicide have shown that hopelessness is often experienced as emotional exhaustion, loss of meaning, and a sense of irreversible psychological defeat (Sun et al., 2025). The present findings therefore reinforce the conceptualization of hopelessness as both a cognitive and

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emotional pathway contributing to adolescent suicide vulnerability.

The findings also demonstrated that emotional numbing significantly predicted suicidal ideation and represented the second most influential variable within the final predictive model. Adolescents with elevated emotional numbing scores reported substantially greater suicidal ideation severity, suggesting that emotional disengagement and restricted affective responsiveness play major roles in youth suicide risk. Emotional numbing may impair emotional processing capacities, reduce adaptive coping mechanisms, and weaken interpersonal attachment systems that normally protect against self-destructive behavior. This finding aligns with emerging research emphasizing the role of emotional emptiness, dissociation, shame, and emotional disconnection in adolescents with histories of suicidal behavior (Rizk-Hildbrand et al., 2025). Emotional numbing may also intensify psychological isolation because emotionally detached adolescents often struggle to communicate distress, seek support, or maintain emotionally meaningful relationships. In this context, emotional numbing may operate as both a trauma-related coping mechanism and a contributor to long-term psychological deterioration. The present findings additionally support literature discussing emerging depressive subtypes characterized by emotional blunting, social disengagement, and affective suppression among adolescents and young adults (Chiappini et al., 2025). Such emotional restriction may progressively reduce resilience and increase susceptibility to suicidal cognition during periods of psychological stress.

Social withdrawal also emerged as a strong predictor of suicidal ideation within the present study. Adolescents experiencing greater interpersonal isolation and reduced social engagement demonstrated significantly higher suicide risk scores. This finding is consistent with attachment-based and interpersonal theories of suicide suggesting that perceived social disconnection and diminished belongingness contribute substantially to suicidal vulnerability (Cassell & Diamond, 2023). Social withdrawal may deprive adolescents of emotional validation, peer support, and relational buffering processes that normally mitigate psychological distress. Over time, withdrawal from interpersonal relationships may reinforce loneliness, cognitive distortions, emotional insecurity, and feelings of invisibility. Prior research has similarly shown that reduced peer connectedness, impaired school belongingness, and diminished family attachment increase the likelihood of suicidal ideation among adolescents exposed to stress and victimization (Dadras & Takashi, 2024; Liu & Liu, 2025). Furthermore, socially withdrawn adolescents may increasingly rely on solitary digital activities and online interactions rather than direct interpersonal communication, which may unintentionally intensify emotional isolation. The present findings therefore highlight the importance of interpersonal connectedness as a protective psychological mechanism within youth suicide prevention efforts.

Another important finding involved the significant relationship between cyberbullying exposure and suicidal ideation. Participants exposed to more severe online harassment demonstrated substantially greater suicidal thinking, and cyberbullying emerged as a meaningful predictor within the machine learning framework. This finding strongly aligns with prior literature documenting the harmful psychological effects of cybervictimization among adolescents and university students (Bezie et al., 2025; Humboldt et al., 2025). Cyberbullying differs from traditional bullying because it can occur continuously across digital platforms, reach large audiences rapidly, and remain permanently accessible online, thereby intensifying humiliation, shame, and emotional distress. The present findings support previous investigations demonstrating that cybervictimization contributes to suicidal ideation through pathways involving hopelessness, psychological pain, depression, and social insecurity (Cao et al., 2025; Liu & Liu, 2025). Similarly, studies examining problematic internet use have shown that adolescents exposed to chronic online victimization frequently experience elevated emotional dysregulation, loneliness, and self-harm behaviors (Lu et al., 2025). Meta-analytic evidence has additionally confirmed that bullying victimization significantly increases suicide risk among youth populations across diverse cultural contexts (Bezie et al., 2025). The present findings therefore reinforce concerns regarding the increasingly harmful psychological impact of digital aggression within contemporary adolescent environments.

A particularly novel finding of the present study was the significant predictive contribution of AI chatbot attachment to suicidal ideation. Adolescents demonstrating stronger emotional attachment to conversational AI systems also exhibited higher levels of suicidal ideation, even after accounting for hopelessness, emotional numbing, social withdrawal, and cyberbullying exposure. Although AI chatbot attachment demonstrated comparatively lower importance scores than the other variables, its predictive significance suggests that emotionally compensatory

technological relationships may represent an emerging psychosocial risk factor among contemporary youth populations. This finding aligns with growing concerns regarding the psychological implications of emotionally immersive AI systems among adolescents (Ohu, 2025; Yu, 2025). Adolescents experiencing loneliness, emotional rejection, or interpersonal insecurity may increasingly rely on AI conversational agents for emotional reassurance and companionship because such systems provide immediate interaction without fear of judgment or rejection. However, excessive emotional dependence on artificial systems may unintentionally reduce motivation for authentic interpersonal engagement and reinforce social withdrawal tendencies. Research examining mental health conversational agents has similarly noted that emotionally vulnerable youth may develop attachment-like relationships with AI systems during periods of distress (Park et al., 2024). Moreover, ethical analyses have warned that AI systems lacking appropriate safeguards may fail to adequately respond to suicidal crises or may unintentionally reinforce maladaptive emotional dependence (Campbell et al., 2025; Ohu, 2025). The present findings therefore contribute to emerging literature emphasizing the need to examine human-AI emotional relationships as psychologically meaningful factors within adolescent mental health research.

The machine learning findings of the present study also have important methodological implications. The stacked ensemble classifier achieved exceptionally high predictive accuracy and outperformed all individual machine learning models. This result supports prior evidence indicating that ensemble learning approaches are highly effective for modeling complex psychological phenomena characterized by nonlinear interactions and multidimensional risk structures (Rodríguez et al., 2023). Suicidal ideation rarely emerges from a single isolated predictor and instead develops through dynamic interactions among emotional, interpersonal, cognitive, and technological variables. Traditional linear statistical models may therefore be insufficient for capturing the complexity of adolescent suicide risk. Ensemble learning methods improve predictive capability by integrating multiple algorithmic perspectives and minimizing overfitting, thereby increasing generalizability across heterogeneous youth populations. The present findings suggest that computational approaches integrating emotional, social, and technological variables may substantially enhance early suicide screening systems and improve identification of high-risk adolescents before severe suicidal crises emerge.

5. Conclusion

The findings of the present study should also be interpreted within the broader sociocultural context of contemporary adolescence. Modern youth populations are increasingly shaped by continuous digital exposure, online social comparison, technological immersion, and rapidly evolving communication environments (Gath, 2026; Marano et al., 2025). These sociotechnological changes may intensify emotional vulnerability by increasing exposure to cybervictimization, unrealistic social standards, emotional overstimulation, and digitally mediated interpersonal insecurity. At the same time, adolescents experiencing emotional distress may seek compensatory attachment through AI systems and online interactions, creating complex feedback loops between technological engagement and psychological functioning. Prior studies have highlighted how internet addiction, social media overuse, and digital immersion contribute to emotional dysregulation, loneliness, and suicidal behavior among youth (Garaigordobil, 2025; Imataka & Shiraishi, 2024). The present findings therefore support the necessity of integrating technological variables into contemporary suicide risk models and adolescent mental health frameworks.

6. Limitations & Suggestions

One limitation of the present study involves its cross-sectional design, which prevents causal interpretation of the observed relationships among emotional numbing, cyberbullying exposure, AI chatbot attachment, hopelessness, social withdrawal, and suicidal ideation. Although the machine learning models demonstrated strong predictive capability, longitudinal investigations are necessary to determine how these variables interact over time in shaping suicide vulnerability trajectories among adolescents. Another limitation involves reliance on self-report measures, which may have introduced response bias, social desirability effects, or underreporting of sensitive psychological experiences. Additionally, the study was conducted among Canadian youth populations and therefore cultural differences may limit generalizability to adolescents from other social and cultural contexts. The assessment of AI chatbot attachment was also based on a newly adapted instrument, and although reliability and content validity were satisfactory, further psychometric validation is needed across diverse populations and technological environments.

Future research should employ longitudinal and multimethod designs to better understand the developmental progression of suicidal ideation in technologically immersed youth populations. Researchers should further investigate the mechanisms through which AI chatbot attachment influences emotional functioning, interpersonal behavior, and suicide vulnerability among adolescents. Additional studies examining moderating variables such as family support, school connectedness, resilience, emotional intelligence, and digital literacy may also improve understanding of protective processes that reduce suicide risk in online environments. Future machine learning studies could incorporate real-time behavioral indicators, ecological momentary assessment methods, and multimodal digital data sources to improve predictive sensitivity and ecological validity. Cross-cultural comparisons would additionally be valuable for examining whether the observed relationships differ across varying technological, educational, and sociocultural contexts.

The findings of the present study have important practical implications for mental health professionals, educators, policymakers, and developers of digital technologies. School-based suicide prevention programs should incorporate interventions targeting hopelessness, emotional numbing, social withdrawal, and cyberbullying experiences while also strengthening emotional regulation and interpersonal connectedness among adolescents. Mental health practitioners should carefully assess adolescents' emotional relationships with AI systems and explore whether excessive technological attachment may reflect underlying loneliness, emotional insecurity, or unmet relational needs. Educational institutions should implement stronger cyberbullying prevention strategies and digital well-being programs that teach healthy online engagement and emotional coping skills. Developers of AI conversational systems should also incorporate evidence-based safety protocols, crisis response mechanisms, and ethical safeguards to reduce potential psychological harm among vulnerable youth users. Finally, the integration of ensemble learning systems into school counseling and public mental health screening programs may substantially improve early identification of adolescents at elevated risk for suicidal ideation and facilitate timely preventive intervention.

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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.

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Authors' Contributions

All authors equally contributed to this article.

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