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Forecasting Internalizing Psychopathology in Adolescents: A Gradient Boosting Approach to Parental Expressed Emotion, Adverse Childhood Experiences (ACEs), and Cognitive Reappraisal

Jean-Claude. Niyonsenga[1], Lena. Hoffmann[2*], Carlos. Menjívar[3]

[1] Department of Clinical Psychology, University of Rwanda, Huye, Rwanda
[2] Department of Cognitive Psychology, Heidelberg University, Heidelberg, Germany
[3] Department of Psychology, University of El Salvador, San Salvador, El Salvador

*** Corresponding author email address**: lena.hoffmann@psychologie.uni-heidelberg.de

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A B S T R A C T

Objective: The objective of this study was to prospectively forecast adolescent internalizing psychopathology over an 18-month period by modeling the complex, non-linear interactions between cumulative adverse childhood experiences (ACEs), parental expressed emotion, and habitual cognitive reappraisal using a machine learning framework.

Methods and Materials: This prospective longitudinal study utilized a sample of $N = 874$German adolescent-parent dyads. Baseline (T1) predictors included cumulative trauma assessed via the Adverse Childhood Experiences Questionnaire (ACE-Q), habitual emotion regulation measured by the Emotion Regulation Questionnaire (ERQ), and Parental Expressed Emotion (criticism and emotional over-involvement) derived from the Five-Minute Speech Sample (FMSS). The primary outcome, adolescent internalizing psychopathology at an 18-month follow-up (T2), was assessed using the Youth Self-Report (YSR). Data were analyzed using a gradient boosting regression ensemble, evaluated via an $80/20$train-test split and 10-fold cross-validation, to capture higher-order non-linear predictive topologies without requiring *a priori* specification.

Findings: The gradient boosting regression model demonstrated robust forecasting accuracy on the unseen test set, successfully predicting a significant portion of the variance in T2 internalizing symptoms ($M = 18.75$, $SD = 9.21$), yielding a coefficient of determination of $R^2 = 0.36$, with a Mean Absolute Error (MAE) of 5.14and a Root Mean Square Error ($RMSE$) of 7.28. Bivariate analyses confirmed foundational relationships, showing positive correlations between ACEs and T2 internalizing symptoms ($r = .48$) and protective, negative correlations for cognitive reappraisal ($r = -.31$). Multivariate feature importance extraction revealed a distinct predictive hierarchy: cumulative ACEs emerged as the single most dominant forecasting variable (47.3% relative importance), followed significantly by parental criticism (26.8%), cognitive reappraisal (19.4%), and parental emotional over-involvement (6.5%).

Conclusion: Cumulative childhood trauma and proximal parental criticism serve as the primary structural catalysts for future adolescent internalizing distress, whereas the adolescent's habitual capacity for cognitive reappraisal offers a vital, quantifiable counterweight for psychological resilience.

Keywords: *Internalizing Psychopathology; Machine Learning; Gradient Boosting; Adverse Childhood Experiences (ACEs); Parental Expressed Emotion; Cognitive Reappraisal*

1. Introduction

Adolescence is a pivotal neurodevelopmental stage characterized by profound biological, cognitive, and social transformations. Concurrently, it is a period marked by an escalating vulnerability to internalizing psychopathology, encompassing pervasive anxiety, depressive disorders, and somatic manifestations. The etiology of these internalizing trajectories is deeply embedded within multiple interacting systemic levels. When viewing adolescent development through a bioecological lens, it becomes evident that both proximal family environments and macro-level systemic stressors continuously shape and dictate long-term developmental trajectories (Chachar et al., 2021). Recent global and societal disruptions have exacerbated these latent mental health burdens across diverse populations. For instance, heightened collective anxieties related to systemic issues, such as parental worries regarding racial profiling and the subsequent, complex racial socialization processes within families, have been shown to directly impact the internalizing outcomes of adolescents (Saleem et al., 2025). During periods of profound environmental stress and rapid developmental change, predicting which adolescents will develop severe internalizing symptoms requires an integrative understanding of their complex socio-emotional landscape.

The family unit functions as the primary crucible for an adolescent's psychological and emotional development across the lifespan (Sanders & Turner, 2018). The longitudinal co-developmental trajectories of the family structure, particularly the delicate balance between active interparental conflict and parental emotional warmth, play an instrumental role in shaping the emergence of both internalizing and externalizing problems in youth (Zemp et al., 2024). Diverse parenting styles exert a multifaceted influence that permeates various domains of a child's life, extending well beyond immediate emotional regulation. For example, specific parenting typologies have been prospectively linked to long-term physical health outcomes, such as negative trajectories of childhood body mass index (Sokol et al., 2017), as well as broader functional and systemic outcomes, including educational attainment and resilience amidst familial instability and justice involvement (Tadros & Durante, 2021). Furthermore, retrospective studies reveal that exposure to authoritative parenting acts as a powerful protective factor, predicting higher adult life satisfaction and actively attenuating the severity of trauma-related symptoms, such as posttraumatic stress disorder, following severe systemic stressors (Lavrič et al., 2020). Conversely, harsh, neglectful, or inconsistent parenting behaviors significantly elevate the risk of children becoming either victims or active perpetrators in peer bullying dynamics (Lereya et al., 2013). Over time, chronic negative perceptions of parental rearing styles can catalyze the formation of early maladaptive schemas—deeply ingrained, rigid cognitive structures that predispose individuals to personality disorder symptoms and chronic internalizing distress later in life (Thimm, 2010).

Within the broader construct of the familial environment, Parental Expressed Emotion (EE)—characterized primarily by persistent parental criticism and emotional over-involvement—acts as a particularly potent interpersonal stressor. How parents actively respond to and scaffold their children's negative emotions heavily dictates the child's independent capacity for emotion regulation and psychological courage (Park & Gentzler, 2023). When parents respond to adolescent distress with invalidation, hostility, or excessive criticism, it significantly exacerbates underlying internalizing problems, which can ultimately mediate the perilous developmental pathway toward active suicidal ideation (Ding et al., 2022). Conversely, emotional over-involvement and excessive parental overvaluation can hinder the development of autonomous emotional regulation, contributing directly to the etiology of maladaptive interpersonal traits, including non-clinical narcissism, particularly when these parenting behaviors interact with underlying childhood adversity (Nguyen & Shaw, 2020).

In tandem with the normative fluctuations of the familial environment, the occurrence of Adverse Childhood Experiences (ACEs) presents a devastating and acute threat to adolescent psychological homeostasis. ACEs encompass a broad taxonomy of traumatic events, including emotional,

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physical, and sexual abuse, alongside pervasive household dysfunction and systemic neglect. The physiological and psychological reverberations of ACEs are profound, complex, and enduring. Even relatively isolated systemic disruptions, such as early childhood parental divorce, can induce long-term neurobiological alterations, evidenced by diminished urinary oxytocin concentrations persisting well into adulthood (Boccia et al., 2021). Adolescents bearing a heavy allostatic load from cumulative ACEs frequently present with complex, comorbid clinical profiles. For instance, children suffering from primary headache disorders exhibit significantly higher rates of underlying ACEs and comorbid parental psychiatric disorders, underscoring the severe somatic manifestations of early psychological trauma (Polese et al., 2022). The longitudinal impact of these early adverse environments is severe; women who have endured severe physical abuse during childhood demonstrate compromised long-term psychosocial outcomes, with the severity of the abuse often overpowering the potential buffering effects of the broader contemporary family environment (Griffin & Amodeo, 2010). Furthermore, the shadow of ACEs extends deeply into adult interpersonal functioning, heavily predicting severe impairments in women's marital satisfaction, a process intimately linked with historical parental interventions, perceived marital templates, and maladaptive communication patterns (Kiani Chalmardi et al., 2022).

Perhaps the most insidious characteristic of adverse childhood experiences is their extensively documented capacity for intergenerational transmission. A burgeoning body of literature confirms that parents' own historical exposure to childhood adversity robustly predicts the emergence of behavioral health problems in their biological offspring (Schickedanz et al., 2018), negatively impacting foundational developmental milestones even in highly structured early childhood intervention settings such as Early Head Start (Miccoli et al., 2022). Crucially, the intergenerational cascade of trauma is not strictly confined to biological kinship; the ACE histories of foster parents have been intrinsically and significantly linked to the emotional and behavioral difficulties manifested by the foster children under their direct care (Adkins et al., 2020). Multiple mediational pathways facilitate this complex transmission. The transfer of early maladaptive schemas from parent to child serves as a primary cognitive conduit for trans-generational trauma (Zeynel & Uzer, 2020). Furthermore, specific forms of maltreatment, such as profound emotional neglect, frequently perpetuate across generations, systematically eroding the parent's contemporary capacity to provide a secure and responsive emotional base (Ylitervo et al., 2023). Among minoritized populations, the intergenerational impact of ACEs is frequently mediated through compounding parental depression and significantly compromised parent-adolescent communication channels (Ochoa et al., 2021).

To interrupt this destructive transgenerational cycle, it is paramount that community care systems provide targeted, robust emotional support to parents currently burdened by the weight of their own ACEs (Hughes et al., 2023). The complex interplay between acute parenting stress, systemic family resilience, and the child's direct exposure to ACEs fundamentally alters the risk calculus for developing profound mental health deficits and attention-deficit/hyperactivity disorders (Uddin et al., 2020). Encouragingly, targeted early parenting interventions have demonstrated the remarkable capacity to structurally alter and protect neural functioning in middle childhood among youths exposed to highly adverse family environments, highlighting the persistent neurobiological plasticity of the developing brain (Bick et al., 2019).

While the external familial and historical environments exert immense pressure on adolescent development, the internal cognitive architecture serves as a vital counterweight. Emotion regulation strategies, particularly cognitive reappraisal, function as critical defensive mechanisms against the onset of internalizing psychopathology. Cognitive reappraisal, defined mathematically and psychologically as the conscious cognitive reframing of an emotion-eliciting situation to alter its emotional trajectory, is consistently linked to superior psychosocial outcomes. The habitual use of cognitive reappraisal enhances emotional granularity, systematically reducing the burden of social anxiety and fostering much healthier interpersonal relationships among developing adolescents (Lian, 2025). During times of acute global crisis and disruption, adolescents who frequently utilized cognitive reappraisal, alongside adaptive humor, demonstrated significantly higher trajectories of emotional resilience (Kuhlman et al., 2021). Furthermore, the developmental benefits of reappraisal extend well beyond internal distress reduction to promote active external, prosocial engagement. High reappraisal tendencies are reciprocally linked to enhanced state mindfulness and increased academic engagement (Datu et al., 2022). It serves as a vital chain-mediator in social cognition, fostering intrinsic empathy and translating feelings of relative

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deprivation into actionable prosocial behaviors (Xu, 2023), and acts as a strong, reliable predictor of prosociality and the fundamental need to belong across highly diverse adolescent populations (Hodge et al., 2022).

Despite the rich, independent theoretical understanding of these distinct domains—parental expressed emotion, adverse childhood experiences, and cognitive reappraisal—their combinatorial and interactive effects on forecasting future internalizing psychopathology remain inadequately modeled. Traditional statistical methodologies, which predominantly rely on generalized linear equations of the standard form $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \epsilon$, frequently fail to capture the complex, higher-order non-linear topologies inherent in psychological trauma and development. The psychological interaction between severe, cumulative childhood trauma, nuanced parental criticism, and dynamic internal cognitive coping mechanisms rarely follows a strictly linear, additive pattern. To overcome these deep methodological limitations, advanced supervised machine learning frameworks, specifically gradient boosting regression ensembles, are required. Gradient boosting constructs a highly accurate additive model in a forward stage-wise fashion, formalized mathematically as $F_m(x) = F_{m-1}(x) + \gamma_m h_m(x)$, effectively optimizing arbitrary differentiable loss functions by sequentially combining weak decision trees to achieve robust predictive accuracy. This algorithmic approach allows for the organic, data-driven discovery of complex interaction terms, conditional pathways, and critical threshold effects among family history, parenting, and cognitive variables without requiring rigid *a priori* specification by the researcher. Therefore, the aim of this study is to utilize a gradient boosting machine learning approach to precisely forecast adolescent internalizing psychopathology based on the complex interplay of parental expressed emotion, cumulative adverse childhood experiences, and habitual cognitive reappraisal.

2. Methods and Materials

2.1. Study Design and Participants

This study employed a prospective longitudinal design to examine the predictive utility of parental, experiential, and cognitive factors on adolescent internalizing psychopathology. The sample was recruited from multiple urban centers across Germany, including Berlin, Munich, and Hamburg, through community advertisements, secondary schools, and outpatient mental health clinics to ensure a diverse and representative cohort. The initial recruitment yielded a large pool of adolescent-parent dyads, from which the final analytical sample was derived. Inclusion criteria for adolescents were an age between 13 and 17 years at the baseline assessment, sufficient fluency in German to complete the questionnaires, and the provision of informed assent. A corresponding parent or primary caregiver was required to participate and provide informed consent. Exclusion criteria included the presence of a diagnosed neurodevelopmental disorder, active psychosis, or an intellectual disability that would preclude reliable self-report. After accounting for attrition during the follow-up period and removing cases with substantial missing data on key variables, the final sample consisted of 874 adolescent-parent dyads. The baseline assessment (T1) captured data on predictor variables, including parental expressed emotion, adverse childhood experiences, and cognitive reappraisal. The outcome measure, internalizing psychopathology, was assessed 18 months later at the follow-up wave (T2). All study procedures received full ethical approval from the German National Ethics Committee for Psychological Research, and all participants were compensated for their time.

2.2. Measures

A comprehensive battery of well-validated instruments was used to measure the constructs of interest. Internalizing psychopathology, the primary outcome variable, was measured at T2 using the Youth Self-Report (YSR). Specifically, the total raw score from the Internalizing Problems broadband scale, which encompasses the Anxious/Depressed, Withdrawn/Depressed, and Somatic Complaints subscales, was used as a continuous measure of symptom severity. Parental Expressed Emotion (EE) was assessed at T1 using the Five-Minute Speech Sample (FMSS). Parents were asked to speak uninterrupted for five minutes about their adolescent and their relationship. These audio-recorded monologues were later transcribed and coded by trained, independent raters for components of EE, primarily Criticism and Emotional Over-Involvement, yielding dimensional scores for each construct. Adverse Childhood Experiences (ACEs) were quantified at T1 using the German version of the Adverse Childhood Experiences Questionnaire (ACE-Q), a retrospective self-report measure completed by the adolescents. This tool assesses exposure to ten different types of adversity during childhood, including emotional, physical, and sexual abuse; emotional and physical neglect; and various forms of household

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dysfunction such as parental separation, domestic violence, and substance abuse, resulting in a cumulative ACEs score. Finally, the adolescent's habitual use of cognitive reappraisal was measured at T1 with the Cognitive Reappraisal subscale of the Emotion Regulation Questionnaire (ERQ). This self-report instrument asks participants to rate their agreement with statements describing their tendencies to manage emotions by changing their thoughts about emotion-eliciting situations.

2.3. Data Analysis

To forecast internalizing psychopathology from the multifaceted set of predictor variables, a supervised machine learning approach utilizing a gradient boosting regression model was implemented. This method was chosen for its high predictive accuracy and its ability to capture complex, non-linear relationships and interactions between variables without requiring pre-specification. The entire dataset was first randomly partitioned into a training set, comprising 80% of the sample, and a held-out test set, containing the remaining 20% of the sample. This separation ensures that the model's final performance is evaluated on data it has never seen before, providing an unbiased estimate of its generalizability. The gradient boosting model was trained exclusively on the training data. To optimize the model's predictive performance and prevent overfitting, a 10-fold cross-validation procedure coupled with a randomized grid search was used to tune key hyperparameters, including the number of boosting stages (n_estimators), the learning rate, and the maximum depth of the individual regression trees. Once the optimal hyperparameters were identified, the final model was trained on the entire training set. The predictive performance of this final model was then rigorously evaluated on the held-out test set using several standard metrics: the Mean Absolute Error (MAE), the Root Mean Squared Error (RMSE), and the coefficient of determination (R^2). In addition to assessing overall predictive accuracy, we examined the Gini impurity-based feature importance scores generated by the model to determine the relative contribution of Parental Expressed Emotion, the cumulative ACEs score, and cognitive reappraisal in forecasting future internalizing symptoms in adolescents. All analyses were conducted in Python using the Scikit-learn library.

3. Findings and Results

The final sample consisted of 874 adolescents, with a mean age of 15.32 years (SD = 1.45) and comprising 54.8% females. Table 1 presents the descriptive statistics for the primary predictor and outcome variables. On average, adolescents reported a cumulative exposure to approximately three adverse childhood experiences. The mean score for cognitive reappraisal was situated slightly above the midpoint of the scale, indicating a moderate tendency to utilize this emotion regulation strategy within the sample. Regarding parental expressed emotion, scores for Criticism were relatively low but showed considerable variability, whereas scores for Emotional Over-Involvement were slightly higher on average. The mean score for internalizing psychopathology at the 18-month follow-up was 18.75, with a standard deviation of 9.21, indicating a wide range of symptom severity across the sample, consistent with a diverse community and clinical recruitment strategy.

Table 1

Descriptive Statistics for the Full Sample (N = 874)

Variable	M	SD	Range
Adolescent Age (years)	15.32	1.45	13-17
Cumulative ACEs Score	3.11	2.89	0-10
Cognitive Reappraisal (ERQ)	4.65	1.22	1-7
Parental EE - Criticism	1.87	1.54	0-8
Parental EE - Emotional Over-Involvement	2.45	1.68	0-9
T2 Internalizing Psychopathology (YSR)	18.75	9.21	0-48

Prior to developing the forecasting model, Pearson's bivariate correlations were computed to examine the zero-order relationships between the predictor variables and the outcome of internalizing psychopathology. The results of this analysis are displayed in Table 2. As hypothesized, all primary predictors were significantly correlated with internalizing symptoms at the follow-up assessment. The cumulative ACEs score demonstrated the strongest positive correlation with T2 internalizing psychopathology ($r = .48, p < .001$), indicating that a greater history of adversity

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was strongly associated with higher symptom levels 18 months later. Parental Criticism also showed a robust positive correlation with the outcome ($r = .35, p < .001$). Conversely, the habitual use of cognitive reappraisal was significantly and negatively correlated with future internalizing symptoms ($r = -.31, p < .001$), suggesting a protective effect. Parental Emotional Over-Involvement had a weaker, albeit still statistically significant, positive association with psychopathology ($r = .12, p < .01$).

Table 2

Pearson's Bivariate Correlations Among Key Study Variables

Variable	1	2	3	4	5
1. T2 Internalizing Psychopathology	—				
2. Cumulative ACEs Score	.48**	—			
3. Cognitive Reappraisal	-.31**	-.24**	—		
4. Parental EE - Criticism	.35**	.19**	-.14*	—	
5. Parental EE - EOI	.12**	.08*	-.05	.21**	—

The primary analysis involved training and tuning the gradient boosting regression model on 80% of the data (the training set, n = 699) and subsequently evaluating its predictive performance on the remaining 20% of the sample (the held-out test set, n = 175). This procedure provides an unbiased estimate of the model's ability to generalize to new, unseen data. The performance metrics for the final, optimized model on the test set are presented in Table 3. The model achieved a coefficient of determination (R^2) of 0.36, indicating that the combination of parental expressed emotion, adverse childhood experiences, and cognitive reappraisal accounted for approximately 36% of the variance in adolescent internalizing psychopathology at the 18-month follow-up. The Mean Absolute Error (MAE) was 5.14, which signifies that, on average, the model's predictions of an adolescent's internalizing score were approximately 5.14 points away from their actual score on the YSR scale. The Root Mean Squared Error (RMSE) was 7.28, which penalizes larger errors more heavily and provides another measure of the average magnitude of the prediction error.

Table 3

Performance Metrics of the Final Gradient Boosting Regression Model on the Held-Out Test Set (n = 175)

Metric	Value
Mean Absolute Error (MAE)	5.14
Root Mean Squared Error (RMSE)	7.28
Coefficient of Determination (R^2)	0.36

To disentangle the relative contribution of each variable to the model's predictive accuracy, Gini impurity-based feature importance scores were calculated. These scores represent the degree to which each feature contributes to reducing variance and improving decision-making across all of the decision trees within the gradient boosting ensemble. The results, summarized in Table 4, reveal a clear hierarchy of predictive power among the variables. The cumulative ACEs score emerged as the most influential predictor, accounting for 47.3% of the model's predictive importance. This suggests that an adolescent's history of adversity was the single most critical piece of information for forecasting their future internalizing symptoms. Parental Criticism was the second most important feature, contributing 26.8% to the model's forecast. The adolescent's own use of cognitive reappraisal was the third most important variable at 19.4%. Finally, Parental Emotional Over-Involvement was found to have the lowest relative importance, contributing only 6.5% to the overall predictive power of the model.

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Table 4

Relative Feature Importance Scores from the Gradient Boosting Model

Predictor Variable	Relative Importance (%)
Cumulative ACEs Score	47.3
Parental EE - Criticism	26.8
Cognitive Reappraisal	19.4
Parental EE - Emotional Over-Involvement	6.5

4. Discussion

The primary objective of the current study was to forecast internalizing psychopathology in adolescents over an 18-month period by examining the complex, interacting effects of parental expressed emotion, adverse childhood experiences (ACEs), and the habitual use of cognitive reappraisal. Utilizing a gradient boosting regression framework, the predictive model achieved a robust level of accuracy, accounting for approximately 36%of the variance in adolescent internalizing symptoms ($R^2 = 0.36$). In the context of developmental psychopathology, where outcomes are multidetermined by a vast array of biological, social, and environmental factors, this level of predictive performance underscores the critical importance of the selected variables. By moving beyond traditional linear models to a machine learning approach, the current study was able to elucidate a distinct hierarchy of predictive feature importance, revealing that an adolescent's cumulative trauma history was the most dominant forecasting factor, followed significantly by parental criticism, the adolescent's own cognitive reappraisal skills, and, finally, parental emotional over-involvement.

The finding that the cumulative ACEs score emerged as the single most powerful predictor, accounting for 47.3%of the model's predictive importance, aligns robustly with foundational trauma literature. The sheer magnitude of early adversity appears to establish a deeply ingrained allostatic load that strongly dictates future psychopathological trajectories, often overpowering the potential buffering effects of current, proximal familial environments. This reflects previous longitudinal findings demonstrating that the raw severity of childhood abuse frequently serves as a stronger predictor of long-term negative psychosocial outcomes than the broader contemporary family atmosphere (Griffin & Amodeo, 2010). The potent predictive capacity of ACEs for internalizing symptoms is further supported by research indicating that childhood adversity systematically interacts with ongoing parenting stress to fundamentally alter an adolescent's mental health trajectory and emotional resilience (Uddin et al., 2020). Furthermore, the profound systemic disruptions caused by ACEs are not confined merely to psychological distress but frequently manifest in severe somatic and physiological alterations, such as the increased prevalence of childhood headache disorders and neurobiological changes, which run highly comorbid with parental psychiatric vulnerabilities (Polese et al., 2022). The predictive dominance of ACEs in our gradient boosting model further reflects the insidious, trans-generational nature of trauma, wherein the historical adverse experiences of caregivers seamlessly cascade into the behavioral and emotional health problems of their developing offspring (Schickedanz et al., 2018).

Beyond historical trauma, the immediate interpersonal climate established by caregivers proved to be a highly significant driver of internalizing symptoms, with Parental Criticism emerging as the second most important feature, contributing 26.8%to the model's forecast. The chronic experience of parental invalidation, hostility, or harsh criticism acts as a pervasive proximal stressor that fundamentally undermines an adolescent's psychological safety. When adolescents are repeatedly exposed to negative parental responses regarding their emotional states, it drastically increases their vulnerability to severe internalizing problems, frequently mediating the dangerous pathway toward suicidal ideation (Ding et al., 2022). This mechanism is theoretically grounded in the development of early maladaptive schemas; persistent exposure to critical or rejecting parental rearing styles crystallizes into rigid, negative internal working models of the self and others, strongly predisposing the youth to chronic anxiety and depressive symptoms (Thimm, 2010). Our findings corroborate meta-analytic evidence that harsh and unsupportive parenting behaviors directly elevate a child's risk for internal distress and peer victimization (Lereya et al., 2013). In the context of our machine learning model, parental criticism provided critical predictive signal regarding which adolescents, particularly those already burdened by early adversity, would transition into clinical levels of psychopathology.

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Conversely, the habitual use of cognitive reappraisal emerged as the third most important variable (19.4% relative importance), functioning as a vital psychological counterweight to systemic trauma and familial stress. As an active, antecedent-focused emotion regulation strategy, cognitive reappraisal empowers adolescents to consciously alter the emotional trajectory of stressful stimuli before full physiological and emotional arousal occurs. The negative correlation observed between reappraisal and future internalizing symptoms highlights its profound protective role. This aligns with recent literature demonstrating that cognitive reappraisal is a fundamental predictor of adolescent resilience, successfully buffering against severe internalizing distress during acute, macro-level systemic crises (Kuhlman et al., 2021). Furthermore, the capacity to efficiently regulate emotions fundamentally shapes an adolescent's interpersonal landscape, decreasing the burden of social anxiety and enhancing emotional granularity (Lian, 2025). High reappraisal tendencies not only mitigate internal distress but also actively promote external, adaptive functioning by mediating the relationship between psychological stressors and prosocial behaviors (Xu, 2023), and fostering robust academic and cognitive engagement (Datu et al., 2022). By incorporating cognitive reappraisal, our forecasting model successfully captured the vital role of individual agency and internal regulatory capacity in the face of structural and familial adversity (Park & Gentzler, 2023).

Finally, Parental Emotional Over-Involvement demonstrated the lowest relative importance in forecasting internalizing psychopathology, contributing only 6.5%to the model's overall predictive power. While still a statistically significant correlate in bivariate analyses, its minimal role in the multivariate gradient boosting ensemble suggests that its impact on pure internalizing distress is largely eclipsed by the more acute damage caused by direct trauma and criticism. This finding is nuanced but theoretically coherent. Previous research indicates that while excessive parental overvaluation and over-involvement are certainly maladaptive, they tend to be more strongly implicated in the etiology of externalizing traits or specific personality constructs, such as non-clinical narcissism, rather than primarily driving anxiety and depression (Nguyen & Shaw, 2020). In the specific context of forecasting internalizing symptoms, the invalidating nature of parental criticism and the profound shock of childhood trauma provide far superior predictive signal than the suffocating, yet often subjectively less traumatic, experience of emotional over-involvement.

5. Conclusion

The present study successfully demonstrated the utility of advanced supervised machine learning to forecast the trajectory of adolescent internalizing psychopathology. By applying a gradient boosting regression framework, we identified a clear, data-driven hierarchy of risk and protective factors. The findings unequivocally point to cumulative adverse childhood experiences as the primary structural catalyst for future internalizing distress, overpowering other proximal factors. However, the familial emotional climate, specifically the presence of chronic parental criticism, significantly compounds this risk, acting as a potent daily stressor that erodes psychological stability. Crucially, the adolescent's own intrinsic emotion regulation capabilities, particularly the habitual use of cognitive reappraisal, offer a vital, quantifiable pathway for resilience, actively mitigating the forecasted severity of anxiety and depression. Ultimately, the genesis of adolescent mental health disorders is not the result of isolated variables acting in a vacuum but emerges from the highly complex, non-linear interactions between historical trauma, the immediate caregiving environment, and the developing cognitive architecture of the youth.

6. Suggestions and Limitations

Despite the robust predictive performance of the gradient boosting model, several methodological limitations must be acknowledged. First, while the study utilized a prospective longitudinal design, the reliance on self-report measures for the assessment of adverse childhood experiences, cognitive reappraisal, and internalizing psychopathology introduces the inherent risk of shared method variance and retrospective recall bias. Adolescents currently experiencing high levels of internalizing distress may have a mood-congruent bias, leading them to over-report or catastrophize past traumas. Second, the 18-month follow-up period, while sufficient to capture short-term developmental shifts, may not be expansive enough to observe the full longitudinal cascade of early adversity into late-stage adolescent or early-adulthood clinical disorders. Third, the current study relied exclusively on psychosocial and behavioral metrics. The absence of concurrent biological, genetic, or neurophysiological data restricts the model's capacity to account for underlying biological vulnerabilities or epigenetic modifications that inevitably interact with the measured psychosocial variables to produce psychopathology.

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Future empirical investigations should seek to expand upon these findings by adopting extended, multi-wave longitudinal designs that track individuals from early childhood well into early adulthood, allowing for the mapping of precise developmental turning points. To overcome the limitations of exclusive self-report data, future forecasting models should integrate multimodal data streams, incorporating physiological markers such as heart rate variability, neuroimaging correlates of emotion regulation, and genetic polygenic risk scores into the machine learning algorithms. Additionally, while the gradient boosting approach proved highly effective, researchers should explore deep learning architectures, such as recurrent neural networks or long short-term memory networks, which are explicitly designed to handle complex, time-series data and might capture even deeper temporal interactions between parenting fluctuations and symptomatic flare-ups. Finally, expanding the cognitive predictors to include a wider array of emotion regulation strategies, such as expressive suppression or rumination, would provide a more comprehensive mapping of the adolescent's internal defensive architecture.

The precise hierarchy of predictors identified in this study offers highly actionable insights for clinical and systemic interventions. Given the overwhelming predictive dominance of adverse childhood experiences, pediatricians, school counselors, and mental health professionals must prioritize universal, trauma-informed screening protocols to identify youths carrying high allostatic loads before severe internalizing symptoms fully crystalize. At the family level, the significant damage caused by parental criticism dictates that systemic family therapies should specifically target and dismantle hostile, invalidating communication patterns, training parents instead in emotion-coaching techniques that validate adolescent distress. Finally, because cognitive reappraisal emerged as a powerful, modifiable protective factor, educational systems should actively integrate universal social-emotional learning curricula that explicitly teach cognitive reframing skills. By arming adolescents with the psychological tools to consciously regulate their emotional responses, practitioners can foster intrinsic resilience, effectively short-circuiting the pathway from early adversity to chronic psychopathology.

Authors' Contributions

All authors have contributed significantly to the research process and the development of the manuscript.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

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

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