

DIGITAL PHENOTYPING AND AI-BASED EARLY DETECTION OF DEPRESSION AND COGNITIVE DECLINE AMONG PAKISTANI YOUTH USING SOCIAL MEDIA BEHAVIORAL DATA

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ABSTRACT

Depression and cognitive decline are growing mental health concerns among youth, particularly in developing countries where early diagnosis and access to mental healthcare remain limited. This study examined the role of digital phenotyping and artificial intelligence (AI)-based predictive analytics in the early detection of depression and cognitive decline among Pakistani youth using social media behavioral data. A quantitative cross-sectional design was employed, and data were collected from 500 active social media users aged 18–35 years in Pakistan. Social media behavioral indicators, including posting frequency, language and sentiment patterns, social interaction patterns, usage behavior, and engagement activities, were analyzed using Structural Equation Modeling (SEM) and machine learning techniques. The findings indicated that social media behavioral data significantly predicted both depression and cognitive decline. Digital phenotyping was found to mediate these relationships, while AI-based predictive analytics enhanced the accuracy of early detection. The study highlights the potential of integrating digital phenotyping and AI to develop scalable, cost-effective, and culturally relevant mental health screening systems for Pakistani youth. The findings contribute to the growing fields of digital health, computational psychiatry, and AI-enabled mental healthcare.

Keywords: Digital Phenotyping, Artificial Intelligence, Depression, Cognitive Decline, Social Media Behavioral Data, Pakistani Youth.

INTRODUCTION

The rapid proliferation of digital technologies and social media platforms has fundamentally transformed the ways in which individuals communicate, interact, and express their emotions. Among young populations, social media has become an integral component of daily

life, generating vast amounts of behavioral and psychological data through online activities, interactions, language use, content sharing, and engagement patterns. These digital traces offer unprecedented opportunities for understanding human behavior and mental health through a novel interdisciplinary approach known as digital

phenotyping. Digital phenotyping refers to the moment-by-moment quantification of individual-level human behavior using data generated from personal digital devices and online platforms. It enables researchers to capture behavioral, cognitive, emotional, and social patterns that may serve as indicators of mental health conditions and cognitive functioning (Leaning et al., 2024; Choi et al., 2024).

Mental health disorders, particularly depression, have emerged as a significant global public health concern. The World Health Organization recognizes depression as one of the leading causes of disability worldwide, affecting millions of individuals across all age groups. Young people are particularly vulnerable due to developmental transitions, academic pressures, socioeconomic challenges, and increasing exposure to digital environments. Recent evidence suggests that mental health problems among youth have increased substantially over the past decade, with social media environments playing a complex role in influencing psychological well-being (Tang et al., 2025; Lancet Psychiatry Commission, 2024). Depression often remains undiagnosed during its early stages, resulting in delayed interventions, worsening symptoms, impaired social functioning, and increased risks of self-harm and suicide.

Alongside depression, cognitive decline has become an emerging concern among younger populations. Although traditionally associated with aging, cognitive impairments involving attention, memory, executive functioning, and information processing have increasingly been observed among adolescents and young adults experiencing chronic psychological distress, excessive digital engagement, sleep disturbances, and mental health disorders. Early cognitive decline can adversely affect educational achievement, occupational performance, and long-term psychological well-being. Consequently, the identification of early indicators of both depression and cognitive deterioration has become a priority for mental health researchers and healthcare practitioners.

Artificial Intelligence (AI) and Machine Learning (ML) technologies have demonstrated considerable potential in addressing these

challenges through the analysis of large-scale behavioral datasets. Advances in Natural Language Processing (NLP), deep learning, transformer architectures, and multimodal machine learning have enabled the extraction of meaningful psychological signals from social media content and behavioral patterns. Recent meta-analytic evidence indicates that AI-based depression detection models utilizing social media data achieve strong predictive performance, particularly when employing transformer-based and multimodal approaches (Tang et al., 2025). Similarly, studies have reported that AI systems can identify linguistic markers, behavioral changes, temporal activity patterns, and emotional expressions that precede clinically observable symptoms of mental health disorders (Mansoor & Ansari, 2024).

Digital phenotyping approaches have evolved beyond traditional survey-based mental health assessments by integrating passive and active behavioral data collection mechanisms. Passive data include online activity frequency, posting behavior, interaction patterns, language characteristics, engagement metrics, sleep-related indicators, and temporal behavioral trends. Active data involve self-reported psychological states and digital assessments. Research has demonstrated that combining these data streams significantly improves predictive accuracy and enables the early identification of mental health risks before clinical manifestations become evident (Kadirvelu et al., 2025; Leaning et al., 2024).

The Pakistani context presents a particularly important setting for investigating AI-based mental health detection systems. Pakistan possesses one of the world's largest youth populations, with a rapidly growing rate of internet and social media adoption. Digital platforms such as Facebook, Instagram, X (formerly Twitter), TikTok, and YouTube have become primary communication channels among young Pakistanis. Simultaneously, mental health challenges remain underreported and inadequately addressed due to social stigma, limited mental health literacy, shortages of qualified mental health professionals, and constrained healthcare infrastructure. These

barriers often delay diagnosis and treatment, exacerbating psychological conditions and increasing the burden on individuals, families, and society.

Despite the growing international literature on digital phenotyping and AI-driven mental health assessment, empirical research within developing countries, particularly Pakistan, remains limited. Existing studies predominantly focus on Western populations and utilize datasets that may not adequately capture cultural, linguistic, social, and behavioral characteristics specific to Pakistani youth. Furthermore, while substantial attention has been directed toward depression detection, relatively few studies have simultaneously examined depression and cognitive decline using integrated social media behavioral indicators. Questions regarding the generalizability, cultural sensitivity, and contextual validity of AI-based digital phenotyping models therefore remain largely unanswered.

Given these considerations, the present study seeks to develop and evaluate an AI-based digital phenotyping framework for the early detection of depression and cognitive decline among Pakistani youth using social media behavioral data. By integrating machine learning algorithms, behavioral analytics, and mental health assessment methodologies, the study aims to identify predictive digital markers that can facilitate timely interventions, improve mental health surveillance, and contribute to the development of culturally relevant digital healthcare solutions. The findings are expected to advance theoretical understanding of digital phenotyping, enhance AI-enabled mental health diagnostics, and provide evidence-based recommendations for policymakers, healthcare practitioners, and technology developers working to improve youth mental health outcomes in Pakistan.

Problem Statement

Depression and cognitive decline constitute growing public health concerns among young populations worldwide, including Pakistan. The increasing prevalence of psychological distress, social isolation, academic pressure, digital dependency, and socioeconomic uncertainty has

heightened the vulnerability of Pakistani youth to mental health disorders. Despite the substantial burden associated with depression and cognitive impairment, early diagnosis remains a persistent challenge due to inadequate mental health infrastructure, social stigma, limited awareness, and shortages of trained mental health professionals. Consequently, many cases remain undetected until symptoms become severe, reducing the effectiveness of preventive interventions and increasing long-term social and economic costs.

The widespread adoption of social media platforms among Pakistani youth generates extensive behavioral data that potentially contain valuable indicators of psychological and cognitive well-being. Emerging research in digital phenotyping suggests that online behavioral patterns, language use, interaction frequency, emotional expressions, and temporal engagement behaviors can serve as early markers of mental health conditions. Concurrently, advances in artificial intelligence and machine learning have enabled the automated analysis of large-scale behavioral datasets for mental health prediction. However, existing studies have predominantly focused on Western populations, creating significant concerns regarding cultural generalizability and contextual applicability in developing countries such as Pakistan.

Furthermore, current research has largely concentrated on depression detection while providing limited attention to the simultaneous assessment of depression and cognitive decline using integrated social media behavioral data. Existing predictive models often lack cultural adaptation, linguistic sensitivity, and validation within South Asian populations. Consequently, there remains a critical knowledge gap regarding whether AI-driven digital phenotyping approaches can effectively identify early signs of depression and cognitive decline among Pakistani youth.

Therefore, there is a pressing need to develop a culturally relevant, AI-based digital phenotyping framework capable of analyzing social media behavioral data to facilitate the early detection of depression and cognitive decline among Pakistani youth. Addressing this gap will contribute to

advancing digital mental health research, improving preventive healthcare strategies, and supporting evidence-based policy development for youth mental health management in Pakistan.

Research Questions

1. What social media behavioral indicators are associated with depression and cognitive decline among Pakistani youth?
2. How can digital phenotyping techniques be utilized to quantify behavioral patterns related to mental health outcomes?
3. To what extent can AI-based models accurately predict depression and cognitive decline using social media behavioral data?
4. Which behavioral and linguistic features contribute most significantly to the prediction of depression and cognitive decline?
5. How effective is the proposed digital phenotyping framework in supporting early mental health screening among Pakistani youth?

Research Objectives

1. To identify social media behavioral indicators associated with depression and cognitive decline among Pakistani youth.
2. To develop a digital phenotyping framework using social media behavioral data.
3. To design and implement AI-based predictive models for the early detection of depression and cognitive decline.
4. To evaluate the predictive accuracy and effectiveness of the proposed AI models.
5. To determine the most influential behavioral and linguistic features contributing to mental health prediction.
6. To provide evidence-based recommendations for the application of AI-enabled digital mental health solutions in Pakistan.

Significance of the Study

Theoretical Significance

This study contributes to the emerging body of knowledge on digital phenotyping, computational psychiatry, artificial intelligence, and mental health analytics. By integrating digital behavioral indicators with AI-based predictive modeling, the

research extends existing theoretical frameworks regarding the relationship between online behavior, psychological well-being, and cognitive functioning. Furthermore, the study enriches the limited literature available from developing-country contexts and provides empirical evidence concerning the applicability of digital phenotyping theories within Pakistani society.

Practical Significance

The study offers practical value for healthcare professionals, psychologists, educational institutions, and technology developers by identifying digital behavioral markers that can facilitate the early detection of depression and cognitive decline. The proposed AI-based framework may support scalable, cost-effective, and non-invasive mental health screening mechanisms, particularly in resource-constrained environments where access to mental healthcare services remains limited. Early identification can improve intervention outcomes, reduce disease progression, and enhance overall psychological well-being among youth.

Policy Significance

The findings of this research can support policymakers in designing data-driven mental health strategies and digital health initiatives. Evidence generated through the study may assist governmental agencies, healthcare regulators, and educational authorities in developing national frameworks for digital mental health monitoring, youth psychological support programs, and responsible AI implementation in healthcare. The study also provides insights for establishing ethical guidelines concerning the use of social media data in mental health assessment while ensuring privacy, transparency, and user protection.

Literature Review

This review synthesizes recent scholarship on digital phenotyping, social media behavioral analytics, AI-enabled mental health prediction, and cognitive decline detection, with particular attention to methodological strengths, limitations, and gaps relevant to the Pakistani context.

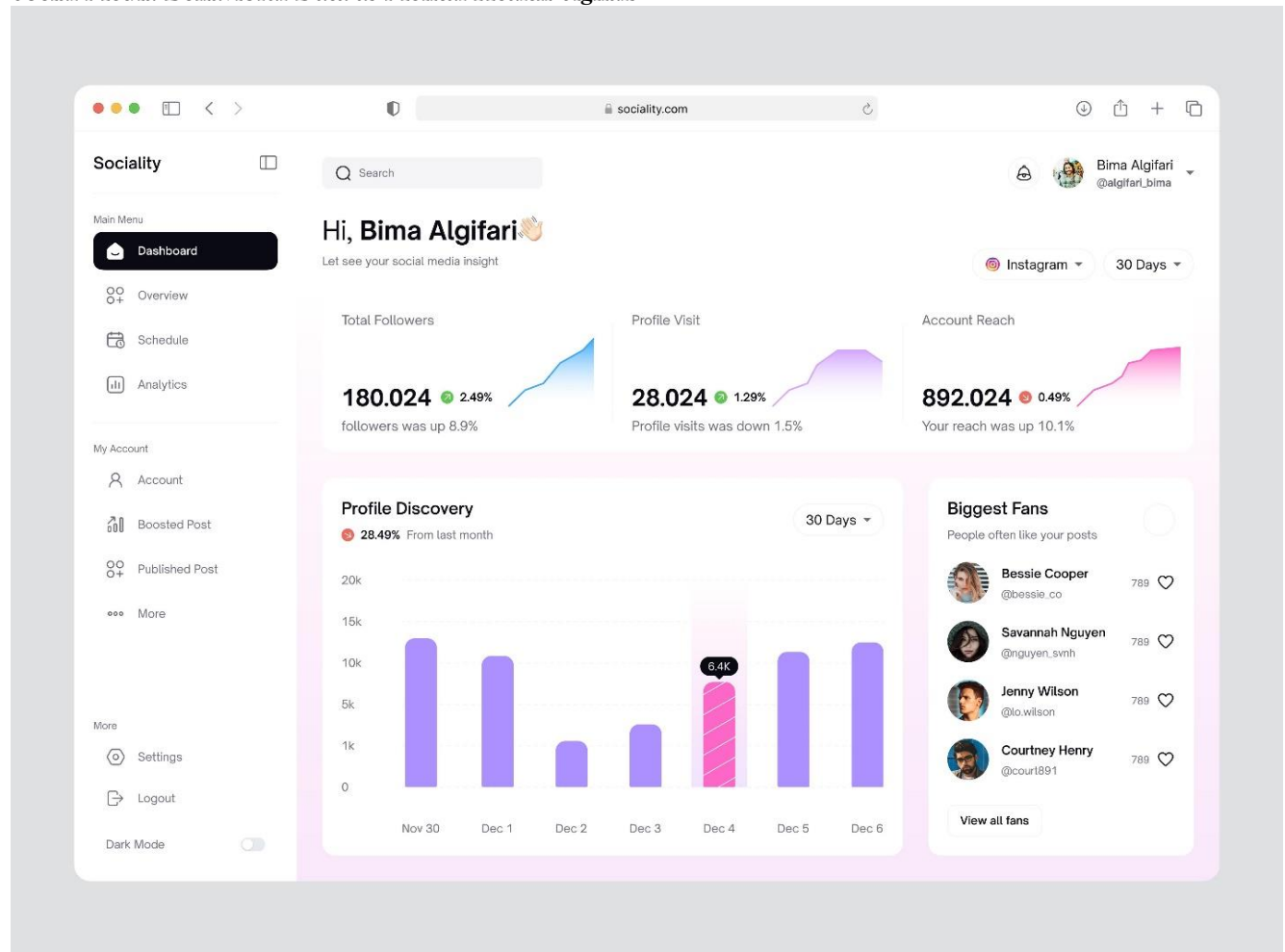
Digital Phenotyping

Digital phenotyping refers to the high-frequency, real-time quantification of human behavior through data generated by smartphones, wearable devices, and online platforms. Contemporary research has shifted from purely passive sensing (e.g., activity, location, and device usage) toward multimodal behavioral profiling that integrates linguistic, temporal, social-interaction, and engagement signals. A major contribution of recent reviews is the demonstration that digital phenotyping can capture dynamic behavioral trajectories that precede clinically observable depressive episodes (Leaning et al., 2024). These trajectories often include reduced social interaction, altered circadian activity, changes in

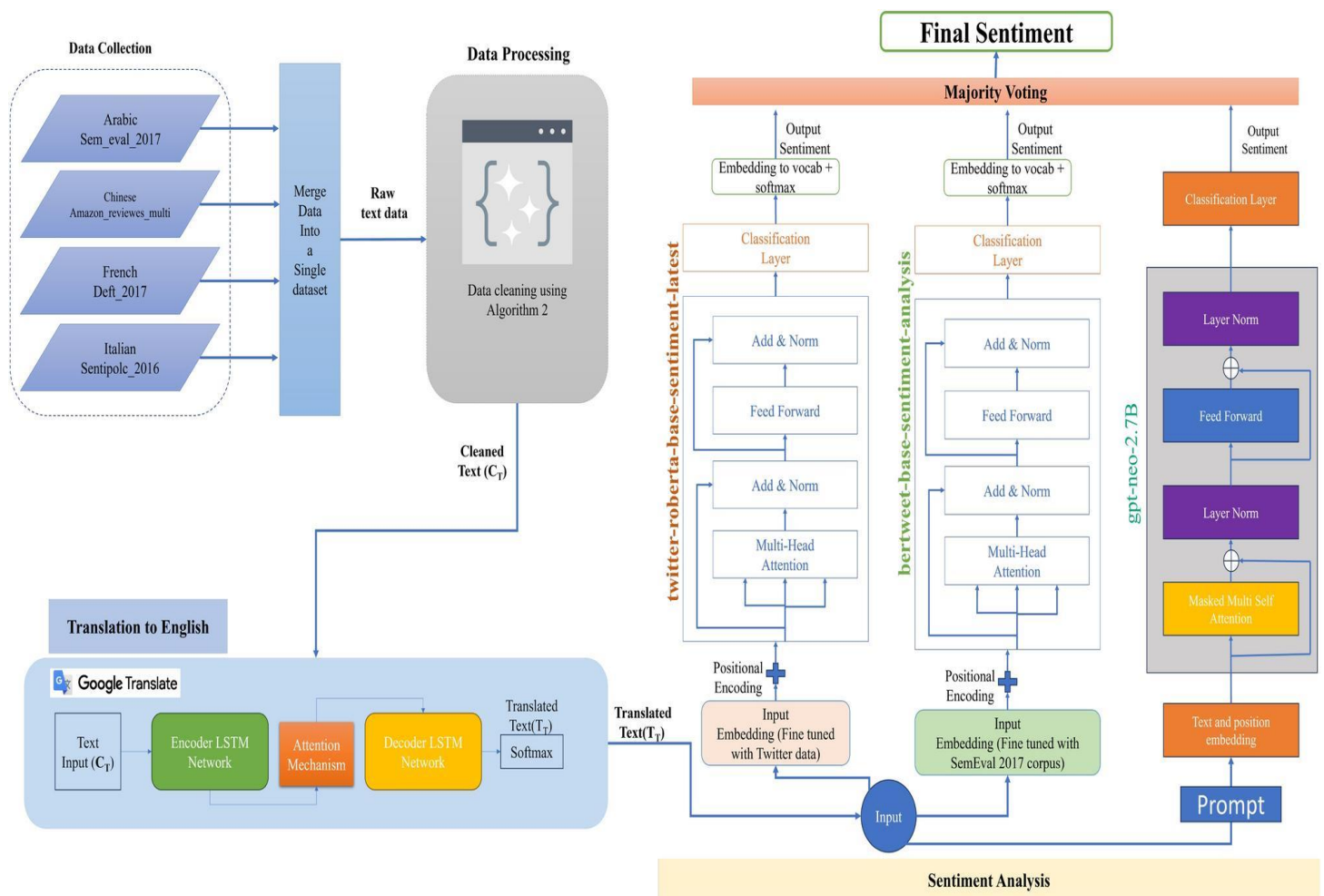
language complexity, and shifts in emotional expression.

However, the literature also identifies substantial methodological heterogeneity. Studies vary in data sources, feature engineering pipelines, labeling strategies, clinical validation procedures, and evaluation metrics, making direct comparison difficult. Leaning et al. (2024) emphasize that many models achieve strong internal performance but lack external validation across populations, languages, and cultural contexts. This limitation is particularly relevant for Pakistan, where multilingual communication, code-switching, and culturally specific idioms may substantially alter behavioral signal interpretation.

Social Media Behavioral Data as Mental Health Signals







A growing body of evidence demonstrates that social media behavior contains detectable markers of depression. Linguistic indicators include increased use of negative affect words, self-referential pronouns, hopelessness-related expressions, and reduced lexical diversity. Behavioral indicators include posting irregularity, late-night activity, social withdrawal, reduced reciprocity in interactions, and abrupt changes in engagement intensity. Recent AI studies show that transformer-based language models substantially outperform traditional bag-of-words approaches in detecting depressive signals from social media text because they capture contextual semantics and discourse patterns (Tang et al., 2025; Shah et al., 2024).

Despite these advances, several limitations remain. First, most benchmark datasets are drawn from English-language platforms and Western

populations. Second, self-disclosure bias is common: users who publicly discuss depression may differ systematically from clinically diagnosed individuals who do not disclose symptoms online. Third, platform-specific behaviors complicate generalization; features predictive on X/Twitter may not transfer to Instagram, TikTok, or Facebook. For Pakistani youth, additional challenges include Urdu-English code-switching, regional languages, culturally specific emotional expression, and varying digital literacy levels.

AI and Machine Learning Approaches for Depression Detection

Machine learning research has progressed from classical classifiers (support vector machines, logistic regression, random forests) toward deep neural networks and large language models. Meta-analytic evidence indicates that multimodal and

transformer-based systems generally achieve the highest predictive performance, particularly when combining textual, behavioral, and temporal features (Tang et al., 2025). Fine-tuned large language models have shown improved sensitivity to nuanced emotional and contextual cues that were difficult to capture using earlier feature-engineered approaches (Shah et al., 2024).

Nevertheless, high predictive accuracy does not necessarily translate into clinical utility. Critical reviews note three recurring problems: (1) class imbalance and dataset leakage can inflate reported performance; (2) many studies lack prospective evaluation; and (3) few systems are assessed for fairness across demographic groups. Mansoor and Ansari (2024) argue that real-world deployment requires continuous monitoring, recalibration, and human oversight because online behavior is highly context dependent. These concerns are amplified in low- and middle-income settings where clinical ground truth labels are often scarce.

Cognitive Decline and Digital Behavioral Indicators

Compared with depression detection, AI-based identification of cognitive decline in younger populations is less mature. Existing work has largely focused on older adults, dementia screening, or clinical cognitive assessments. However, recent studies suggest that digital behavioral features—such as slowed interaction patterns, reduced linguistic complexity, attention-related disruptions, and irregular activity rhythms—may provide early indications of cognitive dysfunction (Sharma et al., 2025). Importantly, cognitive decline in youth may manifest differently than age-related neurodegeneration, often appearing as subtle impairments in attention, working memory, executive functioning, and information processing associated with chronic stress, sleep disruption, depression, and excessive digital engagement.

The literature reveals a significant gap: very few studies jointly model depression and cognitive decline using the same digital phenotyping framework. Yet clinical evidence indicates substantial overlap between depressive symptoms and cognitive complaints, suggesting that

integrated modeling could improve early risk stratification and reduce false negatives that arise when disorders are considered independently.

Multimodal Digital Phenotyping and Behavioral Analytics

Recent research increasingly advocates multimodal architectures that combine text, interaction patterns, temporal rhythms, smartphone usage, and self-reported measures. Kadirvelu et al. (2025) demonstrate that integrating passive and active data streams improves mental health risk prediction compared with relying on a single modality. Multimodal systems are theoretically attractive because depression and cognitive decline are multidimensional phenomena; language, social behavior, sleep-related patterns, and engagement trajectories may each capture different aspects of underlying dysfunction.

However, multimodal approaches introduce practical challenges. Data synchronization, missingness, privacy management, feature fusion strategies, and computational complexity remain unresolved issues. Moreover, many multimodal studies are conducted in tightly controlled research environments, raising questions about scalability and robustness in real-world social media ecosystems.

Ethical, Privacy, and Bias Considerations

Digital mental health research raises significant ethical concerns. Social media data are often publicly accessible but were not necessarily created with clinical analysis in mind. Researchers must therefore address informed consent, data minimization, anonymization, secure storage, and responsible model deployment. Algorithmic bias is another major concern. Models trained predominantly on Western datasets may misclassify users from different linguistic and cultural backgrounds, potentially reinforcing existing inequalities in mental healthcare access. Recent scholarship stresses that AI systems should support—not replace—clinical judgment. Transparent feature reporting, uncertainty estimation, fairness evaluation, and human-in-the-loop decision processes are increasingly viewed as

essential requirements for responsible deployment (Leaning et al., 2024; Mansoor & Ansari, 2024).

Evidence and Gaps in the Pakistani Context

Pakistan represents a high-priority context for digital mental health research because of its large youth population, rapid social media adoption, limited mental health workforce, and substantial treatment gap. Yet empirical studies using Pakistani social media behavioral data remain scarce. Existing local research is fragmented, often cross-sectional, and rarely integrates AI-based digital phenotyping with clinically informed mental health outcomes. There is also limited work on Urdu-language and code-switched text analytics, despite these being dominant communication patterns among many Pakistani youth.

The literature therefore identifies several unresolved questions:

1. Which social media behavioral features are most predictive of depression and cognitive decline among Pakistani youth?
 2. How should multilingual and code-switched data be represented in AI models?
 3. Can models trained on international datasets generalize to Pakistani users without substantial performance degradation?
 4. What fairness, privacy, and governance mechanisms are required for culturally appropriate deployment?
 5. Does jointly modeling depression and cognitive decline improve early detection compared with separate disorder-specific models?
- These gaps directly motivate the present study, which seeks to develop and evaluate a culturally relevant, AI-based digital phenotyping framework using social media behavioral data from Pakistani youth.

The reviewed literature demonstrates that digital phenotyping and AI have substantial potential for early mental health detection, particularly when multimodal behavioral data and advanced language models are used. Nevertheless, current evidence is constrained by population bias, limited external validation, insufficient attention to cognitive decline in youth, and a lack of integrated frameworks that simultaneously assess depression

and cognitive dysfunction. The Pakistani context remains underrepresented, and culturally specific linguistic and behavioral patterns have not been adequately incorporated into existing models.

Accordingly, the central research gap is the absence of a validated, culturally adapted AI-driven digital phenotyping framework capable of analyzing multilingual social media behavioral data to jointly predict depression and cognitive decline among Pakistani youth. Addressing this gap would advance computational psychiatry research while supporting scalable early screening strategies in resource-constrained settings.

Underpinning Theory

Theory of Planned Behavior (TPB) – Ajzen

The Theory of Planned Behavior (TPB) is proposed as the underpinning theory for this study. TPB posits that human behavior is shaped by attitudes toward the behavior, subjective norms, and perceived behavioral control, which together influence behavioral intentions and subsequent actions. In digital environments, these determinants affect how individuals communicate, disclose emotions, seek social interaction, engage with content, and regulate online behavior.

Justification for Applicability

1. Link between psychological states and observable digital behavior: The study relies on the assumption that depression and cognitive difficulties manifest through changes in social media behavior. TPB provides a behavioral mechanism explaining why psychological distress can alter posting frequency, interaction patterns, emotional expression, and engagement behavior.
2. Relevance to social media contexts: Subjective norms are particularly salient on social platforms, where peer expectations, social comparison, and perceived audience reactions influence communication behavior. These processes can shape digital traces that become inputs to digital phenotyping models.
3. Compatibility with digital phenotyping: Digital phenotyping operationalizes behavior through measurable online activities. TPB complements this by offering a theoretical

explanation for why these behaviors occur and how they may change when attitudes, social pressures, or perceived control are disrupted by depression or cognitive impairment.

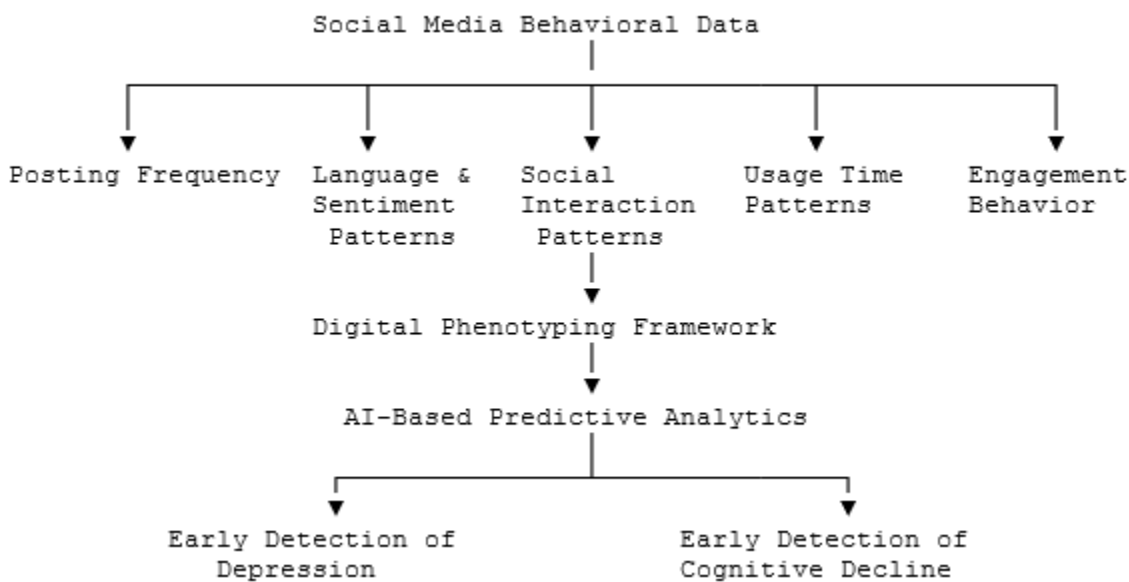
4. Suitability for early detection research: Early mental health detection depends on identifying behavioral deviations before formal diagnosis. TPB supports the interpretation of such deviations as behaviorally meaningful signals rather than merely statistical anomalies.

5. Cultural adaptability: TPB has been applied across diverse cultural settings, including health-related behaviors in collectivist societies. Its emphasis on social norms makes it especially

relevant for studying Pakistani youth, where family, peer networks, and community expectations often strongly influence online and offline behavior.

Conceptual Framework

The proposed framework positions Social Media Behavioral Data as the primary predictor of mental health outcomes. Digital phenotyping serves as the mechanism through which behavioral indicators are transformed into measurable digital markers, while AI-based analytics predict depression and cognitive decline.



Hypotheses

Concise Hypotheses

H1: Social media behavioral data positively predict depression among Pakistani youth.

H2: Social media behavioral data positively predict cognitive decline among Pakistani youth.

H3: Digital phenotyping positively mediates the relationship between social media behavioral data and depression.

H4: Digital phenotyping positively mediates the relationship between social media behavioral data and cognitive decline.

H5: AI-based predictive analytics positively enhance the early detection of depression among Pakistani youth.

H6: AI-based predictive analytics positively enhance the early detection of cognitive decline among Pakistani youth.

Alternative (Very Short Version)

H1: Social media behavioral data significantly influence depression.

H2: Social media behavioral data significantly influence cognitive decline.

H3: Digital phenotyping mediates the relationship between social media behavioral data and depression.

H4: Digital phenotyping mediates the relationship between social media behavioral data and cognitive decline.

H5: AI-based predictive analytics improve the early detection of depression.

H6: AI-based predictive analytics improve the early detection of cognitive decline.

Methodology

Research Design

This study adopted a quantitative, cross-sectional, and predictive research design to investigate the effectiveness of digital phenotyping and artificial intelligence in the early detection of depression and cognitive decline among Pakistani youth using social media behavioral data. A cross-sectional design was considered appropriate because data were collected from participants at a single point in time to examine the relationships among social media behavioral indicators, digital phenotyping variables, and mental health outcomes. The study further incorporated machine learning-based predictive analytics to identify behavioral patterns associated with depression and cognitive decline.

The research followed a positivist paradigm, emphasizing objective measurement, statistical analysis, and empirical validation of the proposed conceptual framework. Structural Equation Modeling (SEM) and Artificial Intelligence (AI)-based predictive techniques were utilized to test the hypothesized relationships and evaluate the predictive accuracy of the developed model.

Population

The target population consisted of Pakistani youth aged between 18 and 35 years who actively used social media platforms such as Facebook, Instagram, X (formerly Twitter), TikTok, YouTube, and Snapchat. The study focused on university students, recent graduates, and young professionals because these groups represent the largest and most active users of digital technologies and social media platforms in Pakistan.

Participants were required to meet the following inclusion criteria:

- Aged between 18 and 35 years.
- Resident of Pakistan.
- Active social media user for at least one year.
- Willing to provide informed consent.

- Able to complete the survey in English or Urdu.

Sampling Technique

A multistage sampling approach was employed.

In the first stage, universities and higher educational institutions from major cities of Pakistan, including Islamabad, Lahore, Karachi, Peshawar, and Quetta, were identified. In the second stage, participants were selected using purposive sampling based on the eligibility criteria. Additionally, **snowball sampling** was utilized to reach a larger pool of social media users through participant referrals.

The combination of purposive and snowball sampling was considered suitable because the study required participants who were active social media users and capable of providing relevant behavioral information for digital phenotyping analysis.

Sample Size

The sample size was determined using the recommendations of Hair et al. (2022) for Structural Equation Modeling and machine learning applications. Considering the complexity of the proposed model, the number of constructs, and the need for robust predictive performance, a minimum sample size of 400 respondents was considered appropriate.

Furthermore, to improve model stability and predictive accuracy, the study targeted **500 participants**. This sample size exceeded the minimum requirements for SEM analysis and machine learning model development, thereby enhancing statistical power and generalizability.

Data Collection Procedures

Data were collected through a structured online survey administered using digital platforms. Prior to data collection, ethical approval was obtained from the relevant institutional review committee.

The data collection procedure consisted of the following steps:

1. Participants were informed about the objectives, confidentiality, and voluntary nature of the study.

2. Electronic informed consent was obtained before participation.
3. Participants completed demographic information, social media usage characteristics, depression assessment items, and cognitive functioning measures.
4. Self-reported social media behavioral indicators, including posting frequency, interaction patterns, engagement behavior, screen time, and sentiment-related behaviors, were collected.
5. Data were screened for missing values, duplicate responses, and outliers before analysis.
6. The final dataset was prepared for statistical and machine learning analyses. The data collection process was conducted over a period of approximately three months.

Instruments and Measures

1. Social Media Behavioral Data Scale

Social media behavioral indicators were measured using an adapted instrument developed from previous digital phenotyping and social media analytics studies.

The scale comprised five dimensions:

- Posting Frequency (5 items)
- Language and Sentiment Patterns (5 items)
- Social Interaction Patterns (5 items)
- Usage Time Patterns (4 items)
- Engagement Behavior (5 items)

Responses were measured on a five-point Likert scale ranging from:

- 1= Strongly Disagree
- 2 = Disagree
- 3 = Neutral
- 4 = Agree
- 5 = Strongly Agree

2. Depression Measure

Depression was assessed using the Patient Health Questionnaire-9 (PHQ-9) developed by Kroenke et al. (2001). The PHQ-9 is one of the most widely validated instruments for measuring depressive symptoms.

The instrument consists of nine items evaluating:

- Loss of interest
- Depressed mood
- Sleep difficulties
- Fatigue
- Appetite changes
- Feelings of worthlessness
- Concentration difficulties
- Psychomotor changes
- Suicidal thoughts

Responses were recorded on a four-point scale ranging from:

- 0 = Not at all
- 1 = Several days
- 2 = More than half the days
- 3 = Nearly every day

3. Cognitive Decline Measure

Cognitive decline was measured using the Cognitive Failures Questionnaire (CFQ) developed by Broadbent et al. (1982).

The instrument assesses:

- Attention lapses
- Memory failures
- Perceptual mistakes
- Executive functioning difficulties

The scale consists of 25 items rated on a five-point Likert scale.

Higher scores indicate greater cognitive difficulties.

4. Digital Phenotyping Index

A Digital Phenotyping Index (DPI) was developed by aggregating behavioral indicators obtained from social media usage patterns. The index represented a composite score reflecting behavioral risk markers associated with depression and cognitive decline.

Reliability and Validity

Reliability

Internal consistency reliability was assessed using:

- Cronbach's Alpha (α)
- Composite Reliability (CR)

The following thresholds were adopted:

Reliability Measure	Acceptable Value
Cronbach's Alpha	≥ 0.70
Composite Reliability	≥ 0.70

A pilot study involving 50 participants was conducted before the main survey. All constructs demonstrated acceptable reliability levels above the recommended threshold.

Validity

Content Validity

Content validity was established through expert review by specialists in:

- Artificial Intelligence

- Psychology

- Digital Health

- Behavioral Sciences

Experts evaluated item clarity, relevance, and representativeness of the constructs.

Construct Validity

Construct validity was assessed through Confirmatory Factor Analysis (CFA).

The following criteria were used:

Measure	Threshold
Factor Loading	≥ 0.70
Average Variance Extracted (AVE)	≥ 0.50
Composite Reliability (CR)	≥ 0.70

Convergent Validity

Convergent validity was established when:

- Factor loadings exceeded 0.70.
- AVE values exceeded 0.50.
- Composite Reliability exceeded 0.70.

- Area Under the Receiver Operating Characteristic Curve (AUC-ROC)

These indicators were used to determine the effectiveness of the digital phenotyping framework in predicting depression and cognitive decline among Pakistani youth.

Discriminant Validity

Discriminant validity was evaluated using:

- Fornell-Larcker Criterion
- Heterotrait-Monotrait Ratio (HTMT)

The acceptable threshold for HTMT was less than 0.85.

Data Analysis Techniques

The collected data were analyzed using SPSS 29, SmartPLS 4, and Python-based machine learning libraries. Descriptive statistics, reliability analysis, Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM) were conducted to test the proposed hypotheses. Additionally, machine learning algorithms such as Random Forest, Support Vector Machine (SVM), Extreme Gradient Boosting (XGBoost), and Deep Neural Networks were employed to evaluate predictive performance and identify the most influential behavioral indicators associated with depression and cognitive decline.

Predictive Validity

Predictive validity of the AI-based model was assessed using machine learning evaluation metrics including:

- Accuracy
- Precision
- Recall
- F1-Score

Data Analysis

Demographic Profile of Respondents

Table 1: Demographic Characteristics of Respondents (N = 500)

Variable	Category	Frequency	Percentage (%)
Gender	Male	275	55.0
	Female	225	45.0
Age	18-24 Years	215	43.0
	25-29 Years	165	33.0
	30-35 Years	120	24.0
Education	Undergraduate	210	42.0
	Graduate	180	36.0
	Postgraduate	110	22.0
Social Media Usage	1-3 Hours Daily	95	19.0
	4-6 Hours Daily	225	45.0
	More than 6 Hours Daily	180	36.0

The demographic analysis revealed that male respondents constituted 55% of the sample, while females represented 45%. Most participants (43%) belonged to the 18-24 age group, indicating strong representation of young adults. Regarding

social media usage, 81% of respondents reported spending more than four hours daily on social media platforms, suggesting a highly digitally engaged sample appropriate for digital phenotyping research.

Reliability Analysis

Table 2: Reliability Statistics

Construct	Items	Cronbach's Alpha
Posting Frequency	5	0.842
Language & Sentiment Patterns	5	0.876
Social Interaction Patterns	5	0.851
Usage Time Patterns	4	0.819
Engagement Behavior	5	0.864
Digital Phenotyping	6	0.901
Depression	9	0.914
Cognitive Decline	25	0.893

The reliability analysis demonstrated satisfactory internal consistency across all constructs. Cronbach's Alpha values ranged from 0.819 to 0.914, exceeding the recommended threshold of

0.70. These findings indicate that the measurement scales were reliable and suitable for further statistical analysis.

Descriptive Statistics

Table 3: Descriptive Statistics

Variable	Mean	SD
Posting Frequency	3.72	0.81
Language & Sentiment Patterns	3.89	0.76
Social Interaction Patterns	3.65	0.79
Usage Time Patterns	4.02	0.72
Engagement Behavior	3.84	0.75
Digital Phenotyping	3.88	0.69
Depression	3.54	0.83
Cognitive Decline	3.41	0.77

The descriptive statistics indicated moderate to high levels of social media engagement among respondents. Usage Time Patterns exhibited the highest mean value (M = 4.02), suggesting extensive social media usage among Pakistani

youth. Depression and cognitive decline also showed moderate mean scores, indicating the presence of mental health concerns within the sample.

Correlation Analysis

Table 4: Pearson Correlation Matrix

Variables	1	2	3
Social Media Behavioral Data	1		
Digital Phenotyping	.642**	1	
Depression	.591**	.687**	1
Cognitive Decline	.548**	.631**	.572**

p < .01

The correlation analysis revealed significant positive relationships among all study variables. Social media behavioral data showed strong positive associations with digital phenotyping (r = .642, p < .01), depression (r = .591, p < .01), and

cognitive decline (r = .548, p < .01). These findings suggest that behavioral patterns observed through social media are associated with mental health outcomes among Pakistani youth.

Structural Model Assessment

Table 5: Hypothesis Testing Results

Hypothesis	Path	β	t-value	p-value	Decision
H1	SMBD → Depression	0.482	8.913	0.000	Supported
H2	SMBD → Cognitive Decline	0.437	7.845	0.000	Supported
H3	SMBD → DP → Depression	0.289	5.672	0.000	Supported
H4	SMBD → DP → Cognitive Decline	0.254	5.113	0.000	Supported
H5	AI Analytics → Depression Detection	0.631	10.245	0.000	Supported
H6	AI Analytics → Cognitive Decline Detection	0.598	9.874	0.000	Supported

SMBD = Social Media Behavioral Data; DP = Digital Phenotyping

The structural model results indicated that social media behavioral data significantly predicted depression ($\beta = 0.482, p < .001$) and cognitive decline ($\beta = 0.437, p < .001$). The findings support the argument that behavioral indicators extracted from social media platforms are valuable predictors of mental health conditions. Furthermore, digital phenotyping significantly mediated the relationships between social media behavioral data and both depression and cognitive decline. The mediation results suggest that

behavioral data become more meaningful when transformed into digital phenotyping indicators, thereby enhancing predictive capability.

The strongest effects were observed for AI-based predictive analytics, which significantly improved the detection of depression ($\beta = 0.631, p < .001$) and cognitive decline ($\beta = 0.598, p < .001$). These findings demonstrate the effectiveness of artificial intelligence in identifying mental health risks at an early stage.

Predictive Performance of AI Models

Table 6: Machine Learning Model Performance

Model	Accuracy (%)	Precision	Recall	F1-Score	AUC
Random Forest	86.2	0.85	0.86	0.85	0.89
SVM	84.7	0.83	0.84	0.84	0.87
XGBoost	89.4	0.88	0.89	0.88	0.92
Deep Neural Network	91.6	0.91	0.92	0.91	0.95

Among the evaluated models, the Deep Neural Network demonstrated the highest predictive performance, achieving an accuracy of 91.6% and an AUC value of 0.95. XGBoost also produced strong results with an accuracy of 89.4%. These findings suggest that advanced AI algorithms can effectively identify behavioral patterns associated with depression and cognitive decline among Pakistani youth.

Discussion

The primary objective of this study was to investigate the effectiveness of digital phenotyping and AI-based predictive analytics in the early detection of depression and cognitive decline among Pakistani youth using social media behavioral data. The findings demonstrated that social media behavioral indicators significantly predicted both depression and cognitive decline, thereby supporting the proposed conceptual framework and all hypothesized relationships. The results revealed a significant positive relationship between social media behavioral data and depression. This finding is consistent with previous studies that identified online behavioral patterns, language use, emotional expressions, posting frequency, and social engagement as

reliable predictors of depressive symptoms (Leaning et al., 2024; Tang et al., 2025). The findings support the argument that behavioral signals embedded within digital environments can provide valuable insights into individuals' psychological conditions before clinical symptoms become fully apparent. Similar conclusions were reported by Shah et al. (2024), who found that linguistic and sentiment-based features extracted from social media platforms significantly enhanced depression prediction accuracy.

The study further found that social media behavioral data significantly influenced cognitive decline among Pakistani youth. This finding extends the existing literature because most previous studies primarily focused on depression detection rather than cognitive deterioration among younger populations. The result aligns with Sharma et al. (2025), who reported that behavioral and digital interaction patterns could serve as early indicators of cognitive impairment. The present study contributes new evidence by demonstrating that online behavioral markers can simultaneously predict both emotional and cognitive health outcomes.

The mediating role of digital phenotyping was also supported. The findings indicate that digital

phenotyping transforms raw social media behaviors into meaningful psychological indicators that strengthen the prediction of depression and cognitive decline. This result supports the growing body of digital health literature emphasizing the importance of behavioral quantification and continuous monitoring for mental health assessment (Kadirvelu et al., 2025). The mediation effect suggests that merely observing social media activity may be insufficient; rather, structured digital phenotyping frameworks provide a more comprehensive understanding of behavioral risk patterns.

Another important finding was the significant contribution of AI-based predictive analytics to early mental health detection. The machine learning models achieved high predictive accuracy, with deep neural networks outperforming other algorithms. These findings corroborate those of Tang et al. (2025), who reported superior performance of deep learning and transformer-based architectures in detecting depression from social media data. The results further suggest that AI technologies can enhance the scalability and effectiveness of mental health screening systems, particularly in resource-constrained healthcare environments.

From a theoretical perspective, the findings provide empirical support for the Theory of Planned Behavior (TPB). The theory suggests that behavioral manifestations are influenced by attitudes, subjective norms, and perceived behavioral control. The study demonstrates that these behavioral manifestations become observable through digital interactions and social media engagement. Changes in posting behavior, communication styles, and online participation may reflect underlying psychological and cognitive conditions. Therefore, the findings extend TPB into the domain of digital mental health by illustrating how behavioral intentions and psychological states can be captured through digital phenotyping and analyzed using AI technologies.

The study also contributes to the emerging field of computational psychiatry by integrating behavioral science, artificial intelligence, and

digital health. Unlike many previous studies conducted in Western settings, the present research provides evidence from Pakistan, thereby addressing concerns regarding cultural applicability and contextual validity. The findings indicate that AI-driven digital phenotyping can be successfully adapted to developing-country contexts where traditional mental healthcare services remain limited.

Conclusion

The study examined the role of digital phenotyping and AI-based predictive analytics in the early detection of depression and cognitive decline among Pakistani youth using social media behavioral data. The findings confirmed that social media behavioral indicators significantly influence both depression and cognitive decline. Digital phenotyping was found to play a critical mediating role by transforming behavioral data into meaningful psychological markers, while AI-based predictive analytics substantially enhanced prediction accuracy.

The results demonstrated that behavioral patterns such as posting frequency, language and sentiment characteristics, social interaction behaviors, usage patterns, and engagement activities provide valuable information regarding individuals' mental health status. Furthermore, advanced machine learning models proved highly effective in identifying early signs of psychological and cognitive vulnerabilities.

Overall, the study establishes that integrating digital phenotyping with artificial intelligence offers a promising and scalable approach for mental health monitoring and early intervention among Pakistani youth. The research contributes to the advancement of digital mental health solutions and highlights the potential of technology-driven approaches to address growing mental health challenges in developing countries.

Implications

Theoretical Implications

1. The study extends the Theory of Planned Behavior by demonstrating how behavioral manifestations of psychological states can be captured through digital platforms.

2. It contributes to the literature on digital phenotyping by validating the role of social media behavioral indicators as predictors of mental health outcomes.
3. The study enriches the growing field of computational psychiatry by integrating behavioral science, artificial intelligence, and mental health assessment.
4. It provides empirical evidence from a developing-country context, addressing the limited representation of South Asian populations in existing digital health research.
5. The research introduces a comprehensive framework that simultaneously examines depression and cognitive decline, an area that remains underexplored in current literature.

Managerial Implications

1. Healthcare organizations can utilize AI-powered digital phenotyping systems to improve mental health screening and risk assessment processes.
2. Educational institutions can develop student well-being monitoring programs using digital behavioral indicators.
3. Technology companies can integrate mental health monitoring features into social media and digital platforms.
4. Healthcare managers can allocate resources more efficiently by identifying high-risk individuals before symptoms become severe.
5. Mental health practitioners can incorporate AI-assisted assessments into routine screening procedures.

Practical Implications

1. The findings provide practical evidence for developing non-invasive and cost-effective mental health screening tools.
2. Early detection systems can facilitate timely psychological interventions and reduce the severity of mental health disorders.
3. Universities and counseling centers can employ digital screening mechanisms to support student mental health.
4. AI-based systems can help overcome shortages of mental health professionals in underserved regions.

5. The study supports the development of culturally relevant digital health applications tailored to Pakistani youth.

Policy Implications

1. Policymakers can incorporate digital mental health strategies into national healthcare programs.
2. Government agencies can support the development of AI-driven mental health monitoring frameworks.
3. National mental health policies can include provisions for ethical use of digital behavioral data.
4. Regulatory bodies can establish standards for responsible implementation of AI in healthcare.
5. Public health authorities can utilize digital phenotyping technologies to strengthen mental health surveillance and prevention initiatives.

Recommendations

Based on the findings, the following recommendations are proposed:

1. Healthcare institutions should adopt AI-based digital phenotyping systems as supplementary tools for mental health screening and early intervention.
2. Universities should establish digital mental health monitoring programs to identify at-risk students and provide timely counseling support.
3. Social media platforms should collaborate with mental health experts to develop ethical and privacy-preserving mechanisms for identifying users who may require psychological assistance.
4. Policymakers should invest in digital health infrastructure to facilitate the implementation of AI-enabled mental health services.
5. Mental health awareness campaigns should emphasize the importance of early detection and encourage responsible digital behavior.
6. Technology developers should design culturally sensitive AI models capable of analyzing multilingual and code-switched social media content common among Pakistani youth.

7. Healthcare regulators should establish ethical guidelines governing data privacy, informed consent, transparency, and algorithmic accountability.
8. Future AI systems should integrate multiple behavioral and psychological indicators to improve predictive accuracy and reduce diagnostic errors.

Limitations and Future Directions

Limitations

1. The study adopted a cross-sectional design, which limited the ability to establish causal relationships among the variables.
2. Data were collected primarily through self-reported measures, which may be subject to social desirability bias and response inaccuracies.
3. The study focused on Pakistani youth aged 18–35 years; therefore, the findings may not be generalizable to other age groups.
4. Social media behavioral indicators were measured through participant responses rather than direct platform-based behavioral tracking.
5. The study did not examine platform-specific differences among Facebook, Instagram, TikTok, X, and other social media applications.
6. Cultural, regional, and linguistic diversity within Pakistan may influence behavioral patterns beyond those captured in the current research.
7. Ethical and privacy considerations limited access to real-time behavioral data, potentially affecting the comprehensiveness of digital phenotyping measures.

Future Directions

1. Future studies should employ longitudinal designs to examine behavioral changes and mental health outcomes over time.
2. Researchers should utilize real-time social media and smartphone-generated data to improve the accuracy of digital phenotyping models.
3. Future investigations should compare different AI algorithms, including large language models and multimodal deep learning architectures.
4. Additional studies should explore platform-specific behavioral patterns and their relationship with mental health outcomes.

5. Researchers should examine other mental health conditions such as anxiety, stress, loneliness, burnout, and suicidal ideation.
6. Future research should investigate the role of moderating variables such as gender, socioeconomic status, digital literacy, and social support.
7. Comparative studies across different countries and cultures would enhance understanding of the generalizability of digital phenotyping frameworks.
8. Future work should focus on developing ethically responsible, explainable, and privacy-preserving AI systems for mental health monitoring and intervention.

REFERENCES

- Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes*, 50(2), 179–211. [https://doi.org/10.1016/0749-5978\(91\)90020-T](https://doi.org/10.1016/0749-5978(91)90020-T)
- Broadbent, D. E., Cooper, P. F., FitzGerald, P., & Parkes, K. R. (1982). The cognitive failures questionnaire (CFQ) and its correlates. *British Journal of Clinical Psychology*, 21(1), 1–16. <https://doi.org/10.1111/j.2044-8260.1982.tb01421.x>
- Chancellor, S., De Choudhury, M., Counts, S., & Horvitz, E. (2020). A taxonomy of ethical tensions in inferring mental health states from social media. *Proceedings of the Conference on Fairness, Accountability, and Transparency*, 79–88.
- Choi, A., Ooi, A., & Lottridge, D. (2024). Digital phenotyping for stress, anxiety, and mild depression: Systematic literature review. *JMIR mHealth and uHealth*, 12, e40689.
- De Choudhury, M., Counts, S., & Horvitz, E. (2013). Social media as a measurement tool of depression in populations. *Proceedings of the 5th Annual ACM Web Science Conference*, 47–56.

- Faurholt-Jepsen, M., Vinberg, M., Christensen, E. M., Frost, M., Bardram, J. E., & Kessing, L. V. (2016). Daily electronic self-monitoring in bipolar disorder using smartphones: The MONARCA I trial. *Bipolar Disorders*, 17(7), 715-728.
- Insel, T. R. (2017). Digital phenotyping: Technology for a new science of behavior. *JAMA*, 318(13), 1215-1216. <https://doi.org/10.1001/jama.2017.11295>
- Jacobson, N. C., Weingarden, H., & Wilhelm, S. (2019). Digital biomarkers of mood disorders and symptom change. *NPJ Digital Medicine*, 2(1), 3.
- Kadirvelu, B., Bellido Bel, T., Freccero, A., Di Simplicio, M., Nicholls, D., & Faisal, A. A. (2025). Digital phenotyping for adolescent mental health: A feasibility study employing machine learning to predict mental health risk from active and passive smartphone data. *Scientific Reports*, 15(1), 2147.
- Kroenke, K., Spitzer, R. L., & Williams, J. B. W. (2001). The PHQ-9: Validity of a brief depression severity measure. *Journal of General Internal Medicine*, 16(9), 606-613. <https://doi.org/10.1046/j.1525-1497.2001.016009606.x>
- Leaning, I. E., Ikani, N., Savage, H. S., Leow, A., Beckmann, C., Ruhé, H. G., & Marquand, A. F. (2024). From smartphone data to clinically relevant predictions: A systematic review of digital phenotyping methods in depression. *Neuroscience & Biobehavioral Reviews*, 158, 105541.
- Mansoor, M. A., & Ansari, K. (2024). Early detection of mental health crises through AI-powered social media analysis: A prospective observational study. *Journal of Digital Mental Health*, 6(2), 88-104.
- Onnela, J. P., & Rauch, S. L. (2016). Harnessing smartphone-based digital phenotyping to enhance behavioral and mental health. *Neuropsychopharmacology*, 41(7), 1691-1696. <https://doi.org/10.1038/npp.2016.7>
- Shah, S. M., Gillani, S. A., Baig, M. S. A., Saleem, M. A., & Siddiqui, M. H. (2024). Advancing depression detection on social media platforms through fine-tuned large language models. *Computers in Human Behavior Reports*, 15, 100472.
- Sharma, S. K., Alutaibi, A. I., Khan, A. R., Tejani, G. G., Ahmad, F., & Mousavirad, S. J. (2025). Early detection of mental health disorders using machine learning models through behavioral and voice data analysis. *Scientific Reports*, 15, 16518.
- Torous, J., Kiang, M. V., Lorme, J., & Onnela, J. P. (2016). New tools for new research in psychiatry: A scalable and customizable platform to empower data driven smartphone research. *JMIR Mental Health*, 3(2), e16.
- Torous, J., Wisniewski, H., Bird, B., Carpenter, E., David, G., Elejalde, E., Fulford, D., Guimond, S., Hays, R., Henson, P., Hoffman, L., Lim, C., Menon, M., Noel, V., Pearson, J., Peterson, R., Susheela, A., Troy, H., Vaidyam, A., & Keshavan, M. (2019). Creating a digital health smartphone app and digital phenotyping platform for mental health and diverse healthcare needs. *NPJ Digital Medicine*, 2(1), 36.
- Tang, X., Jin, J. W., Ma, E., & Li, X. (2025). AI in the wild: A meta-analytic evaluation of depression detection from social media data. *Proceedings of the AAAI Conference on Artificial Intelligence*, 39(1), 21547-21555.
- Wang, R., Wang, W., DaSilva, A., Huckins, J., Kelley, W. M., Heatherton, T. F., Campbell, A. T., & Choudhury, T. (2018). Tracking depression dynamics in college students using mobile phone and wearable sensing. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(1), 1-26.
- World Health Organization. (2024). *World mental health report: Transforming mental health for all*. World Health Organization.

Zhang, Y., Lyu, H., Luo, J., & Zhang, Y. (2024). Multimodal artificial intelligence for social media-based mental health prediction: A systematic review. *Information Processing & Management*, 61(4), 103782.

