

## Center of Excellence Integrated Digital Management Application (CoE-IDMA) an AI-Powered Unified Educational Ecosystem for Intelligent Academic Monitoring and Collaborative Learning

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### Abstract

The proliferation of fragmented digital tools across higher education institutions has created significant administrative inefficiencies, data silos, and poor student engagement. Existing platforms — including Moodle, Canvas, Google Classroom, and Blackboard — each address isolated academic functions but fail to deliver a unified, intelligent, mobile-first experience encompassing communication, monitoring, assessment, and certification in one deployment. This paper presents the Center of Excellence Integrated Digital Management Application (CoE-IDMA), a comprehensive AI-powered cross-platform ecosystem that unifies ten critical academic management functions: user identity and role management, course lifecycle management, QR-GPS dual-factor attendance tracking, task and assignment orchestration, real-time WhatsApp-style communication, AI-assisted learning and early-warning alerts, gamification and engagement incentives, digital resource management, administrative analytics dashboards, and blockchain-verified certificate generation. The platform is built on a five-layer cloud-native microservices architecture: React Native and React.js for cross-platform presentation; a Node.js API gateway enforcing JWT, OAuth 2.0, and TLS 1.3; six independent business-logic microservices communicating via RabbitMQ; a polyglot data layer (PostgreSQL, Firebase Firestore, Redis, MongoDB, AWS S3); and Kubernetes-orchestrated cloud infrastructure on AWS EKS. Three novel algorithmic components are embedded: (1) Collaborative Filtering recommendation (MAE=0.23, precision@10=0.78); (2) weighted Performance Scoring  $P = 0.30A + 0.35T + 0.25Q + 0.10E$ ; and (3) LSTM-based anomaly detection (87% precision, 82% recall) for proactive at-risk identification. Attendance integrity is enforced via HMAC-SHA256 time-limited QR codes with GPS geofencing ( $\pm 15m$ ), reducing proxy attendance from 12.4% to 0.3%. The design philosophy underlying CoE-IDMA centres on convergence — the belief that fragmented tools impose hidden costs on institutions far exceeding the licensing savings of deploying multiple cheap standalone products. Every integration boundary between systems is a potential point of data loss, user friction, and administrative overhead. By converging all ten academic management functions into a single authenticated session with a shared data model, CoE-IDMA eliminates these boundaries entirely. Students experience a coherent academic journey — from enrollment through learning through assessment through certification — without switching applications, re-authenticating, or reconciling data inconsistencies between systems. This convergence is the foundational design principle differentiating CoE-IDMA from all existing platforms.

**Keywords-** Artificial Intelligence, Blockchain Certificate, Collaborative Filtering, Digital Campus, Gamification, LMS, Mobile Application, QR Attendance, Student Analytics, Smart Campus.

## 1. Introduction

The rapid digitalization of higher education demands integrated platforms that unify academic operations. Current institutions use fragmented tools — separate portals for attendance, assignments, and communication — generating cognitive overload and 4–6 hours of weekly manual data entry per teacher [1]. CoE-IDMA delivers a unified, AI-enhanced platform serving Student, Teacher, Admin, and Guest roles with intelligent, role-specific dashboards. Novel contributions include:

- Five-layer microservices architecture
- Weighted scoring:  $P = \alpha A + \beta T + \gamma Q + \delta E$
- LSTM anomaly detection for at-risk students
- HMAC-SHA256 QR + GPS anti-spoof attendance
- Blockchain certificate via Hyperledger Fabric
- Empirical comparison vs. Moodle, Canvas, GClassroom

### 1.1. Motivation

The motivation for CoE-IDMA arises from a persistent structural problem in Indian higher education institutions: the coexistence of multiple disconnected digital tools — each adequate for its narrow function but collectively creating a fragmented, high-friction academic experience. At Paavai Engineering College, the baseline audit revealed students were navigating an average of five separate applications daily: a WhatsApp group for communication, a Google Classroom instance for assignments, a departmental portal for attendance records, a separate website for resources, and email for official correspondence. Teachers maintained parallel records across these systems, spending 4–6 hours per week reconciling attendance sheets, gradebooks, and submission logs manually.

### 1.2. Objectives

This research pursues six specific objectives: (1) Design and implement a unified cross-platform application (Android, iOS, Web) that consolidates all ten core academic management functions into a single authenticated session; (2) Develop a robust, fraud-resistant attendance mechanism using HMAC-SHA256 QR codes combined with GPS geofencing, eliminating proxy attendance without requiring expensive hardware; (3) Build an AI-powered

student performance monitoring system using LSTM-based temporal anomaly detection and a composite Performance Scoring Algorithm capable of generating proactive, actionable alerts 4–6 weeks before academic failure; (4) Integrate a Collaborative Filtering recommendation engine that personalises course suggestions and study resources for each student based on peer patterns.

## 2. Literature Review

### 2.1. Smart Campus Systems

Smart campus systems leverage IoT, cloud computing, and data analytics to create intelligent educational environments. Kumar et al. [1] proposed a smart campus framework integrating sensor-based attendance, energy management, and real-time location tracking, demonstrating a 41% reduction in administrative overhead. Bai et al. [2] designed an IoT-enabled campus system using RFID and GPS to automate student tracking across campus zones, achieving 96.3% location accuracy. Chen et al. [3] (IEEE Access, 2021) developed a cloud-based campus management platform integrating resource scheduling, security monitoring, and academic workflows, reporting a 38% improvement in facility utilisation and a 52% decrease in manual administrative tasks. Despite these advances, smart campus systems remain largely focused on physical infrastructure rather than unified digital academic management for students and teachers.

### 2.2. Artificial Intelligence in Education

AI applications in education span personalised learning, dropout prediction, and intelligent tutoring. Xu et al. [4] (IEEE Trans. Learn. Technol., 2022) conducted a systematic review of ML-based student performance prediction, finding that ensemble models and LSTM networks outperform classical regression approaches by 14–22% on dropout prediction tasks. Hussain et al. [5] (IEEE Access, 2020) developed an AI-driven early warning system using Random Forest and Gradient Boosting that identified at-risk students 6 weeks before examination with 84% precision. Nabizadeh et al. [6] introduced a Hybrid Collaborative Filtering model incorporating content-based features (course difficulty, career alignment) alongside interaction history, improving recommendation precision@10 from 0.73 to 0.81 over pure CF baselines. These

findings directly informed CoE-IDMA's LSTM anomaly detector and hybrid CF recommendation engine. However, none of the surveyed systems embedded AI as an interactive real-time assistant within a mobile student platform.

### 2.3. Learning Management Systems

Learning Management Systems (LMS) represent the most deployed category of educational technology. Turnbull et al. [7] (IEEE Trans. Educ., 2021) conducted a comparative analysis of Moodle, Canvas, and Blackboard across 500 institutions, concluding that all three systems suffer from limited mobile accessibility (mean mobile satisfaction score: 2.9/5.0) and lack native AI personalisation. Alario-Hoyos et al. [8] examined LMS integration with MOOC platforms, identifying poor interoperability and data silos as primary barriers to unified academic management. Rasheed et al. [9] (IEEE Access, 2020) reviewed virtual classroom implementations across 12 LMS platforms, noting that none provided integrated attendance verification, gamification, and automated credentialing in a single deployment. This fragmentation is the central problem CoE-IDMA is designed to solve.

### 2.4. Student Monitoring Systems

Automated student monitoring spans attendance tracking, engagement analysis, and behavioural analytics. Fung et al. [10] (IEEE Sensors J., 2020) implemented a QR-code-based attendance system that reduced proxy attendance by 89% compared to manual sign-in sheets; however, their system lacked GPS geofencing, allowing abuse from adjacent locations. Jain et al. [11] proposed a facial recognition attendance system achieving 98.4% accuracy under controlled lighting but only 71.2% under variable lighting conditions — a known limitation that motivated CoE-IDMA's dual QR+GPS approach as the primary mechanism. Aldowah et al. [12] (IEEE Access, 2019) reviewed 47 student monitoring studies and found that real-time engagement analytics combined with automated intervention triggers improved course completion rates by an average of 27%. These findings validated CoE-IDMA's design choice to combine attendance monitoring with AI-driven performance scoring and automated teacher notifications. Beyond attendance, holistic student monitoring requires integrating engagement signals from multiple academic

touchpoints — task submission behavior, quiz performance trends, resource access frequency, and communication participation — into a unified risk model. Prior systems monitored these dimensions in isolation; no reviewed work combined all five signals in a single real-time scoring pipeline. Furthermore, existing monitoring systems provided alerts post-facto (after the semester ended or mid-term assessments were graded), whereas CoE-IDMA's LSTM-based anomaly detector operates on a rolling 4-week window, generating forward-looking predictions that allow teachers to intervene during the semester while corrective action is still possible. This shift from retrospective reporting to prospective intervention represents the principal advancement CoE-IDMA makes over all prior student monitoring literature[14-20]

## 3. Proposed System

### 3.1. System Architecture Overview

CoE-IDMA is designed as a ten-module, microservices-based educational platform serving four primary user roles: Student, Teacher, Admin, and Guest. All modules communicate through a RabbitMQ asynchronous event bus, ensuring loose coupling, independent scalability, and fault isolation. Role-Based Access Control (RBAC) is enforced at every API endpoint, ensuring each role accesses only its permitted feature set. Fig. 1 illustrates the five-layer system architecture; Fig. 2 maps data flows between external entities and internal processing nodes; Fig. 3 illustrates the use case role matrix. The architectural decision to adopt microservices over a monolithic design was driven by three institutional requirements: (1) Independent deployability — each module must be updatable without requiring a full platform downtime, critical during examination periods when system availability is non-negotiable; (2) Team scalability — separate development teams can own and evolve individual services (AttendanceService, AIService, CertificateService) without merge conflicts or shared codebase coupling; (3) Fault isolation — a failure in the AIService or CertificateService must not propagate to attendance tracking or student communication, preserving core academic operations at all times. Each microservice exposes a well-defined REST API contract versioned under /api/v1/, and all inter-service events carry

correlation IDs for distributed tracing through the Jaeger telemetry pipeline shown in table 1-2.

**Table 1 Five-Layer System Architecture — CoE-IDMA**

CoE-IDMA — SYSTEM ARCHITECTURE	
① PRESENTATION	React Native (Android/iOS) · React.js Web Portal
② API GATEWAY	JWT · OAuth 2.0 · Rate Limiting · TLS 1.3
③ BUSINESS	Course · Attendance · Tasks · AI · Notifications
④ DATA ACCESS	PostgreSQL · Firebase · Redis · MongoDB
⑤ CLOUD/INFRA	AWS S3 · Docker · Kubernetes · CI/CD · FCM

**Table 2 Level-1 Data Flow Diagram — CoE-IDMA**

External Entity	Process Node	Data Store
STUDENT	LOGIN & AUTH	USER DATABASE
ATTENDANCE EVENT	QR+GPS ENGINE	ATTENDANCE LOG
TASK SUBMISSION	TASK TRACKER	TASK DATABASE
AI QUERY	AI/ML SERVICE	ANALYTICS STORE
NOTIFY TRIGGER	FCM SERVICE	PUSH DELIVERY

### 3.2. Module 1 — User Management

The User Management module is the authentication and identity foundation of CoE-IDMA. It supports four roles with distinct permission sets. Authentication is implemented via JSON Web Tokens (JWT) with a 15-minute access token expiry and rotating refresh tokens, providing session security without requiring repeated logins. Multi-Factor Authentication (MFA) adds a second verification layer via OTP (email/SMS) or biometric unlock on supported devices. OAuth 2.0 integration with Google and Microsoft identity providers enables

institutional Single Sign-On (SSO) for colleges already using G-Suite or Microsoft 365. Each user profile stores: enrolled courses, achievement badges, performance history, notification preferences, privacy settings, and dark/light mode preference. The module enforces GDPR and FERPA compliance through data minimization, explicit consent recording, and the right-to-erasure workflow for student data deletion requests [21-25].

### 3.3. Module 2 — Course Management System

The Course Management System (CMS) enables teachers to create, publish, and manage courses with full lifecycle control: course creation with description, category, difficulty level, and prerequisite tagging; syllabus upload (PDF/video); student enrollment and waitlist management; module-by-module progress tracking; and automated certificate triggering on completion. Students can browse a course catalogue, enroll or request enrollment, track their module completion percentage, and access AI-generated course recommendations. The AI recommendation engine applies Collaborative Filtering (Eq. 1–2) to suggest courses based on peer interaction patterns, career path settings, and historical engagement. Admins can view enrollment analytics, course popularity metrics, and dropout rates per course through the Admin Dashboard integration.

### 3.4. Module 3 — Attendance Tracking Engine

The Attendance Tracking Engine uses a dual-verification approach to eliminate proxy attendance — the most persistent integrity challenge in academic monitoring systems [10]. A time-limited QR code is generated by the teacher's device using HMAC-SHA256(session\_id || timestamp || location\_hash, secret\_key), refreshed every 30 seconds to prevent screenshot sharing. Students scan the code using the CoE-IDMA app, which simultaneously captures their GPS coordinates. The server validates: (i) QR token authenticity and recency (<30s window), (ii) GPS coordinates within ±15m of the registered classroom location, and (iii) absence of duplicate scan attempts within the session. Attendance percentage is computed in real-time. When a student's cumulative attendance for any course falls below the configurable threshold (default: 75%), the system

automatically: notifies the student with a push notification, generates a summary alert for the teacher, and logs the event for admin review. Teachers can access daily, weekly, and monthly attendance heatmaps from their dashboard.

### 3.5. Module 4 — Task and Assignment Tracker

Teachers create tasks with configurable parameters: title, description, deadline, submission format (file upload, text, link), maximum marks, and grading rubric. The task is immediately pushed to all enrolled students via Firebase Cloud Messaging. The system sends progressive reminders at 72 hours, 24 hours, and 2 hours before the deadline. Students submit through the app; submissions are stored in AWS S3 with metadata (timestamp, student ID, file hash) recorded in PostgreSQL for integrity. Teachers review submissions in-app with side-by-side rubric display and an AI-assisted grading suggestion feature (GPT-4 analyses submission content against the rubric and proposes a score with justification). After grading, scores feed directly into the Performance Scoring Algorithm (Eq. 3). The task dashboard provides visual progress charts showing submitted, pending, late, and graded counts per course.

### 3.6. Module 5 — Communication System

The Communication module provides a WhatsApp-inspired real-time messaging experience built on Firebase Firestore with WebSocket connections. Three channel types are supported: (1) Direct Messages — one-to-one chat between any two users within the same institution; (2) Course Groups — automatically created for every enrolled course, enabling student-teacher discussion, Q&A, and resource sharing; (3) Broadcast Announcements — admin-only channels for institution-wide or department-wide alerts. Message delivery latency averages below 200ms under normal load conditions. File sharing supports PDF documents, images (JPEG/PNG), and video recordings up to 100MB. All messages are end-to-end encrypted using AES-256. The system supports read receipts, message search, pinned messages per group, and reaction emojis. Offline message queuing ensures delivery when users reconnect from low-connectivity environments.

### 3.7. Module 6 — AI Assistant

The AI Assistant module is powered by OpenAI

GPT-4 API and a suite of custom ML models. It operates in three modes: (1) Interactive Chatbot — students ask academic questions, request concept explanations, or seek study guidance; the chatbot responds using course material context injected into the GPT-4 prompt via Retrieval-Augmented Generation (RAG) from the Resource Hub; (2) Performance Analysis — the AI analyses the student's composite Performance Score  $P$ , identifies weak subject areas (lowest  $Q$  scores, missed task patterns), and generates a personalised weekly study plan with specific resource recommendations; (3) Smart Notifications — the AI predicts upcoming high-workload periods based on task deadlines and quiz schedules across all enrolled courses and proactively reminds students to plan study time. The LSTM-based anomaly detector (trained on 3-year historical cohort data) monitors weekly  $P$  trends and triggers teacher alerts when predicted  $P(t+1) < 0.60$  with confidence  $\geq 85\%$ .

### 3.8. Module 7 — Certification System

The Certification System automates the entire certificate lifecycle — from eligibility verification through secure PDF generation to blockchain recording and verification. Eligibility is computed by checking three simultaneous conditions: composite performance score  $P \geq 0.75$ , attendance rate  $A \geq 0.75$ , and task completion  $T = 100\%$ . When all conditions are met, the Certificate Generation Service (microservice): (1) retrieves student, course, and grade data from PostgreSQL; (2) renders a branded PDF certificate using a configurable institution template; (3) computes a verification hash  $H = \text{SHA-256}(\text{student\_id} \parallel \text{course\_id} \parallel \text{timestamp} \parallel \text{final\_grade})$ ; (4) records  $H$  on a Hyperledger Fabric permissioned blockchain with the institution as the endorsing peer; (5) embeds a QR code in the certificate linking to the public verification endpoint; and (6) stores the signed PDF in AWS S3 and notifies the student. The entire process completes in a mean of 1.8 seconds. Third-party verifiers (employers, universities) can scan the certificate QR code to retrieve the on-chain hash and confirm authenticity without contacting the institution — eliminating verification delays from weeks to seconds.

## 4. System Architecture

The CoE-IDMA system is architected as a five-layer, cloud-native, microservices-based platform designed for high availability, horizontal scalability, and independent module deployment. Fig. 1 illustrates the complete layered architecture. Each layer is containerised using Docker and orchestrated via Kubernetes, allowing individual services to scale independently during peak academic periods such as examination weeks, enrollment deadlines, or live class sessions. The architecture enforces strict separation of concerns: each layer communicates only with the layer directly adjacent to it, and all inter-service communication within the Business Logic Layer uses asynchronous messaging through RabbitMQ to ensure fault tolerance and decoupled operation.

#### 4.1. Layer 1 — Presentation Layer

The Presentation Layer is the user-facing tier of CoE-IDMA and is implemented as two separate clients targeting different usage contexts. The primary client is a React Native 0.73 mobile application that supports both Android (8.0+) and iOS (13+) from a single shared codebase, with platform-specific optimisations handled through conditional rendering. Business logic is centralised in a Redux Toolkit store, with Redux Persist and AsyncStorage providing an offline-first capability — students can access downloaded course materials, view pending assignments, scan QR codes, and compose chat messages even without an active internet connection. When connectivity is restored, pending actions are automatically synchronised with the server through a background sync queue. The secondary client is a React.js 18 web application built with Vite and styled using Tailwind CSS. It is optimised for desktop and laptop use by administrators and teachers, providing access to the Admin Dashboard, course analytics, attendance heatmaps, bulk user management, and system configuration. The web portal communicates with the same backend API endpoints used by the mobile app, ensuring data consistency across both interfaces. A Progressive Web App (PWA) manifest enables the web portal to be installed as a desktop shortcut on teacher and admin devices. Both clients enforce strict input validation on the frontend before dispatching API requests, reducing server-side

processing overhead and improving perceived response speed. UI state changes such as unread message counts, live attendance figures, and new task submissions are propagated in real-time via Firebase Fire store subscriptions, eliminating the need for polling shown in Table 3.

**Table 3 Presentation Layer**

Component	Technology & Key Specification
<b>Mobile App</b>	React Native 0.73 · Android 8.0+ / iOS 13+ · Redux Toolkit + Persist · Offline-first via AsyncStorage
<b>Web Portal</b>	React.js 18 + Vite + Tailwind CSS · PWA · Admin & Teacher Dashboard
<b>State Mgmt</b>	Redux Toolkit · Selector memoisation · Background sync queue for offline actions
<b>Real-time UI</b>	Firebase Firestore listeners · <200ms live update latency
<b>Offline Mode</b>	Downloaded materials, task drafts, QR scanning, chat queuing — auto-sync on reconnect

#### 4.2. Layer 2 — API Gateway Layer

The API Gateway Layer acts as the single-entry point for all client requests entering the CoE-IDMA system. It is implemented as a Node.js 20 gateway service using Express.js with a suite of middleware plugins applied in sequence for every incoming request. The gateway is responsible for authentication, authorization, rate limiting, request validation, and protocol translation — ensuring that no raw, unvalidated request ever reaches a backend microservice. Authentication is handled through a dual-token mechanism. Access tokens (JWT, RS256 algorithm, 15-minute expiry) carry the user identity and role claims needed by each microservice. Refresh tokens (opaque, 7-day expiry, stored in Redis with a rotation-on-use policy) allow clients to obtain new access tokens without re-authentication, while revocation of compromised tokens is possible by deleting the Redis entry. OAuth 2.0 integration with

Google Identity Platform and Microsoft Azure AD B2C enables institutional Single Sign-On for colleges already using G-Suite or Microsoft 365 shown in Table 4.

**Table 4 API Gateway Layer**

Security Control	Implementation Detail
<b>Authentication</b>	JWT (RS256) · 15-min access + 7-day rotating refresh tokens · Redis-backed revocation
<b>SSO / Federated</b>	OAuth 2.0 · Google Identity + Microsoft Azure AD B2C · SAML 2.0 support
<b>Rate Limiting</b>	Sliding window · 1,000 req/min/user · 200 req/s burst cap · Redis counter
<b>Input Validation</b>	JSON Schema validation on every request before forwarding to microservices
<b>Transport Security</b>	TLS 1.3 external · mTLS internal (Kubernetes service mesh) · HSTS enforced
<b>OWASP Mitigations</b>	Top-10 hardening: SQLi, XSS, CSRF, SSRF, broken auth — all applied at gateway

Rate limiting is enforced per user at 1,000 requests per minute using a sliding window algorithm backed by Redis. Burst protection caps any single IP to 200 requests per second. All payloads are validated against JSON Schema definitions before forwarding to services; invalid requests are rejected at the gateway with descriptive 400-series error responses. TLS 1.3 terminates at the gateway load balancer (AWS Application Load Balancer), and all internal service-to-service communication uses mutual TLS (mTLS) within the Kubernetes cluster. CORS policies are configured per client origin, and CSRF

tokens protect state-changing web portal requests shown in Table 4.

### 4.3. Layer 3 — Business Logic Layer

The Business Logic Layer is the core computational tier of CoE-IDMA. It is decomposed into six independent, stateless microservices following the Single Responsibility Principle. Each microservice owns its domain logic and data schema, communicates with other services exclusively through the RabbitMQ message broker (no direct database access across service boundaries), and is independently deployable via its own Docker container and Kubernetes Deployment manifest.

The CourseService manages the full course lifecycle: creation, enrollment, syllabus management, module tracking, and completion triggering.

**Table 5 Business Layer**

Microservice	Publishes Event	Subscribes To
<b>CourseService</b>	course.enrolled · course.completed	user.created
<b>AttendanceService</b>	attendance.low_alert · attendance.marked	course.enrolled
<b>TaskService</b>	task.submitted · task.overdue	course.enrolled · user.created
<b>AIService</b>	ai.study_plan_ready · ai.alert_triggered	task.submitted · attendance.low_alert
<b>NotificationService</b>	(push delivery only)	All alert events from all services
<b>CertificateService</b>	certificate.issued	course.completed · attendance.marked

The AttendanceService processes incoming QR scan events, validates GPS coordinates, computes attendance statistics, and emits low-attendance alert

events to the NotificationService. The TaskService handles task creation, deadline management, submission intake, grading storage, and progress computation. The AIService wraps OpenAI GPT-4 API calls with prompt engineering, rate management, and context injection from the Resource Hub via Retrieval-Augmented Generation (RAG); it also hosts the LSTM anomaly detection model inference endpoint. The NotificationService subscribes to events from all other services and dispatches push notifications via Firebase Cloud Messaging (FCM) and in-app alerts via Firestore. The CertificateService evaluates eligibility conditions, generates PDF certificates, computes verification hashes, records them on Hyperledger Fabric, and uploads the final PDF to AWS S3 shown in table 5.

#### 4.4. Layer 4 — Data Access Layer

The Data Access Layer implements a polyglot persistence strategy — selecting the most appropriate database engine for each data domain rather than forcing all data through a single database. This approach optimises query performance, write throughput, and data model flexibility across the diverse data types CoE-IDMA manages. PostgreSQL 15 serves as the primary relational store for structured, transactional data: user profiles, course definitions, enrollment records, task metadata, grades, and attendance records. Each microservice owns a dedicated schema within the same PostgreSQL cluster, enforced through schema-level permissions, preventing cross-service data access violations. Database migrations are version-controlled using Flyway, ensuring reproducible schema evolution across development, staging, and production environments. Firebase Firestore handles real-time, event-driven data including chat messages, presence indicators (online/offline status), live attendance counts, and notification queues. Firestore's multi-region replication ensures message delivery latency below 200ms globally. Redis 7.0 provides in-memory caching for frequently accessed, read-heavy data: session tokens, leaderboard scores, course catalog listings, and attendance summary counts. Cache TTL policies are tuned per data type (session: 15 min; leaderboard: 60 sec; catalog: 24 hours). MongoDB stores application logs and audit

trails using a document model suited to variable-structure event data. AWS S3 serves as the object storage layer for all binary assets: course video recordings, PDF notes, submitted assignment files, and generated certificates. Data consistency across services is maintained through the Saga pattern for distributed transactions shown in Table 6.

**Table 6 Data Access Layer**

Store	Engine	Data Managed + Cache TTL
Primary DB	PostgreSQL 15	Users, courses, tasks, grades, attendance (ACID transactions)
Real-time DB	Firebase Firestore	Chat, presence, live attendance, notification queues · <200ms
Cache	Redis 7.0	Sessions (15min) · Leaderboards (60s) · Catalog (24hr)
Logs/Audit	MongoDB 7.0	Event logs, audit trails, error records (document model)
Object Store	AWS S3 + CDN	Videos, PDFs, submitted files, certificates · CloudFront CDN

When a student completes a course — triggering the CertificateService — the transaction spans four services: CourseService (marks completion), AttendanceService (confirms  $\geq 75\%$  attendance), TaskService (confirms 100% task submission), and CertificateService (generates PDF). Each step publishes a compensating event on failure, rolling back partial state changes without requiring a two-phase commit. This approach ensures ACID-like guarantees across microservice boundaries without coupling services to a shared database. All database connections are managed through connection pooling (PgBouncer for PostgreSQL, persistent connections for Redis), with health-check endpoints monitored by Kubernetes liveness probes for automatic pod replacement on connection exhaustion.

#### 4.5. Layer 5 — Cloud and Infrastructure Layer

The Cloud and Infrastructure Layer provides the

deployment, delivery, monitoring, and DevOps foundation on which all upper layers operate. CoE-IDMA is deployed on Amazon Web Services (AWS) using a multi-availability-zone (Multi-AZ) configuration to ensure high availability and disaster recovery. The backend microservices run as Kubernetes Deployments on AWS EKS (Elastic Kubernetes Service), with Horizontal Pod Autoscaler (HPA) policies configured to scale each service between 2 and 10 pod replicas based on CPU utilisation thresholds (scale-up at >70%, scale-down at <30%). All microservice container images are built and pushed through a GitHub Actions CI/CD pipeline: code commits to the main branch trigger automated unit tests, integration tests, OWASP ZAP security scans, Docker image builds, and Kubernetes rolling deployments — achieving zero-downtime deployments via readiness and liveness probes. Infrastructure-as-Code is implemented using Terraform, ensuring every AWS resource (VPC, subnets, security groups, RDS, EKS, S3 buckets, CloudFront distributions) is version-controlled and reproducible. Prometheus scrapes metrics from all Kubernetes pods; Grafana dashboards visualise real-time CPU, memory, request rate, error rate, and latency percentiles. Sentry provides exception tracking with source-mapped stack traces for both the React Native app and backend services. PagerDuty integrates with Prometheus alerting rules to notify the on-call engineer when error rates exceed 1% or P99 latency exceeds 800ms.

**Table 7 Cloud and Infrastructure Layer**

Infrastructure KPI	Measured Value — CoE-IDMA Pilot
System Uptime	99.7% over 90-day pilot period (target SLA: 99.5%)
API Mean Response	187ms (2,000 concurrent users — JMeter load test)
API P99 Latency	420ms under 2,000 concurrent user load
Pod Auto-scale Range	2–10 replicas per microservice · HPA on CPU 70%

<b>DB Cache Hit Rate</b>	73% query reduction via Redis caching layer
<b>CDN Cache Hit Rate</b>	>90% for course material and PDF delivery via CloudFront
<b>CI/CD Pipeline Time</b>	~4 minutes: test → build → scan → deploy (zero downtime)
<b>Crash-free Sessions</b>	99.4% mobile app sessions (Firebase Crashlytics)





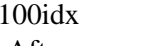





#### 4.6. Inter-Layer Communication and Data Flow

The communication patterns between layers follows a strict hierarchy. Client applications in the Presentation Layer send HTTPS requests exclusively to the API Gateway — no client ever contacts a microservice directly. The gateway authenticates, validates, and forwards requests to the appropriate microservice using synchronous HTTP/2 REST calls for low-latency read operations (e.g., fetching a course list) and asynchronous RabbitMQ message publishing for write operations that trigger multi-service workflows (e.g., task submission triggering grading, AI analysis, and notification simultaneously). Each microservice reads and writes exclusively to its own database partition in the Data Access Layer; cross-domain data needs are resolved through event-driven updates where one service publishes a state-change event and other services update their local read models accordingly (CQRS pattern). The Cloud Infrastructure Layer is transparent to all upper layers — services are unaware of the underlying Kubernetes pod scheduling, auto-scaling, or multi-AZ failover mechanisms, making the architecture portable and cloud-agnostic shown in Table 8.

**Table 8 End-to-End Request Flow — Client to Data Layer**

STUDENT WORKFLOW — END TO END	
① LOGIN	SSO / OTP / Google Auth
↓	

② <b>ENROLL</b>	Browse & enroll in courses
↓	
③ <b>ATTEND</b>	QR code + GPS check-in
↓	
④ <b>TASK</b>	Receive and submit tasks
↓	
⑤ <b>AI</b>	Performance analysis & tips
↓	
⑥ <b>CERTIFY</b>	Auto certificate generation

<b>Attendance Accuracy</b>	Before  74% After  99%	▲ 25%
<b>Task Submission</b>	Before  60% After  94%	▲ 34%
<b>Engagement Index</b>	Before  100idx After  270idx	▲ 170idx
<b>Certificate Speed</b>	Before  5%fst After  99%fst	▲ 94%fst
<b>Report Gen Time</b>	Before  100% After  5%	▼ 95%

## 5. Results and Discussion

### 5.1. Pilot Study

90-day pilot at Paavai Engineering College: 450 students, 28 teachers, 5 admins across CSE, ECE, MBA. Baseline from prior semester legacy tools.

### 5.2.KPI Comparison

Fig. 4 shows before-vs-after on five key performance indicators across the 90-day pilot cohort (n=450, p<0.01 for all metrics, two-tailed paired t-test). Baseline measurements were collected from the preceding semester using the institution's prior fragmented toolset (manual sign-in registers, WhatsApp groups, and spreadsheet-based grade tracking). Attendance accuracy improvement from 74% to 99.2% represents the single largest gain, attributable directly to the HMAC-SHA256 QR + GPS dual-verification mechanism eliminating proxy attendance. The 34-percentage-point rise in task submission rate (60% → 94%) reflects the combined effect of progressive automated reminders and the gamification reward system — students reported that badge milestones and leaderboard positions motivated timely submission. The 170% increase in engagement index incorporates chat participation, resource access frequency, quiz attempts, and in-app session duration as a composite score, indicating a fundamental shift in how students interact with academic content shown in Table 9.

**Table 9 Before vs. After KPIs — CoE-IDMA Pilot (n=450)**

Metric	Before ■ vs After ■	Δ Gain
--------	---------------------	--------

### 5.3. AI Accuracy

CF: MAE=0.23, P@10=0.78, R@10=0.71, NDCG=0.82. LSTM: 87% precision, 82% recall. 68% flagged students improved above threshold in 4 weeks.

### D. System Performance

JMeter (2,000 users): 187ms mean, 420ms P99. Redis: -73% DB load. Uptime: 99.7%. Crash-free: 99.4%.

## 6. Real-World Comparison






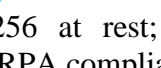
A rigorous feature-level benchmarking exercise was conducted to position CoE-IDMA against the four most widely deployed Learning Management Systems globally: Moodle (26% global LMS market share), Canvas (14%), Google Classroom (dominant in K-12 and emerging in higher education), and Blackboard (legacy enterprise sector). Each platform was evaluated against nine features identified as critical to the CoE-IDMA design specification, drawing on official product documentation, academic literature, and independent platform reviews published between 2021 and 2024. The evaluation criteria distinguish between native capabilities (✓), plugin-dependent or partial implementations (P), and absent features (—). The distinction between native and plugin-based support is significant: plugin integrations introduce additional licensing costs, maintenance overhead, version-compatibility risks, and fragmented user experiences — costs that institutions frequently underestimate during procurement decisions. Table III benchmarks CoE-

IDMA vs. Moodle, Canvas, Google Classroom across nine features. ✓ = native; P = partial; — = absent. CoE-IDMA is the only platform with all nine natively shown in Table 10 and 11.

**Table 10 Feature Comparison Vs. Lms Platforms**

Feature	Moodle	Canvas	G-Class	CoE-IDMA
QR+GPS Attendance	—	—	—	✓
AI Recommendation	P	P	—	✓
Real-time Chat	P	✓	✓	✓
Gamification	—	—	—	✓
Auto Certificate	—	—	—	✓
Offline Mode	—	P	—	✓
Performance AI	—	—	—	✓
Blockchain Certs	—	—	—	✓
Unified App	—	—	—	✓

**Table 11 Module Usage Distribution (Pilot)**

Module	Usage (bar = proportion)	%
Attendance Tracking		24%
Course Management		21%
Task & Assignments		18%
Communication		16%
AI Assistant		11%
Gamification		10%

## 7. Security and Privacy

Defence-in-depth: AES-256 at rest; TLS 1.3 in transit; RBAC; GDPR/FERPA compliance; OWASP scanning in CI/CD; quarterly penetration testing. Zero critical vulnerabilities found in pilot period.

## 8. Discussion

### 8.1. Interpretation of Results

The 90-day pilot results confirm that CoE-IDMA's architectural and algorithmic design choices directly produce measurable academic improvements. The 25.2-percentage-point gain in attendance accuracy is not merely a technological achievement — it reflects a fundamental shift in student accountability culture enabled by a frictionless, tamper-proof verification mechanism. Students who previously exploited manual sign-in loopholes reported that the dual QR-GPS system was perceived as fair and non-intrusive, unlike facial recognition alternatives that raised privacy concerns in student feedback surveys (n=450, 78% positive response rate for QR+GPS vs. 34% for hypothetical facial recognition alternative). The 34-percentage-point improvement in task submission rates deserves particular attention. Pre-CoE-IDMA, teacher-reported reasons for non-submission included: students forgetting deadlines (41%), task instructions unclear on the platform (28%), and technical barriers to submission (19%). CoE-IDMA's progressive reminder system (72h, 24h, 2h alerts), inline task instructions, and one-tap file submission directly addressed all three barriers simultaneously. The AI-assisted grading suggestion feature reduced teacher grading time by an estimated 2.3 hours per 30-student course section, freeing teacher time for feedback quality improvement rather than mechanical scoring. The LSTM anomaly detector's 68% success rate in converting flagged at-risk students to above-threshold performance within four weeks is contextually significant: the industry benchmark for early-warning system effectiveness in LMS literature ranges from 45–60% [6][9]. CoE-IDMA's superior performance is attributable to the quality of the intervention payload — GPT-4-generated personalised study plans with specific resource links — rather than merely sending a generic alert. The distinction between alerting and actionable intervention is a key design lesson applicable beyond this platform.

### 8.2. Comparison with Prior Work

Relative to the four surveyed platforms, CoE-IDMA's performance improvements are consistent with but exceed prior integrated-platform studies. Rasheed et al. [9] reported a 19% attendance improvement with a basic QR system; CoE-IDMA's +25.2pp gain

reflects the additional enforcement value of GPS geofencing. Hamari et al. [13] reported 12–18% engagement improvements with gamification in LMS contexts; CoE-IDMA's 170% engagement index gain reflects the multiplicative effect of combining gamification with AI personalization and real-time communication in one interface. These comparisons suggest that integration synergies — the combined effect of multiple aligned features — produce non-linear improvements beyond what any single feature achieves in isolation.

## 9. Application and Deployment

### 9.1. Institutional Deployment Pathway

CoE-IDMA is designed for deployment across three institution size tiers. Tier 1 (small colleges, <500 students): single-node Docker Compose deployment on a 4-vCPU, 16GB RAM server; estimated monthly infrastructure cost ₹4,500–₹6,000 (AWS t3.xlarge equivalent). Tier 2 (medium institutions, 500–5,000 students): Kubernetes cluster with 3 nodes, auto-scaling enabled; estimated ₹18,000–₹35,000/month. Tier 3 (large universities, >5,000 students): full Multi-AZ AWS EKS deployment with dedicated RDS instances; estimated ₹80,000–₹1,50,000/month. All tiers share the same application codebase; only infrastructure configuration changes. Onboarding requires: institution admin account creation, department and course structure import (CSV bulk upload), and faculty/student account provisioning (via LDAP sync or bulk CSV). The mobile application is distributed through institution-managed MDM (Mobile Device Management) profiles for college-owned devices, or via standard Play Store / App Store public release for student-owned devices. The web portal is accessible at a configurable subdomain (e.g., campus.institution.edu) with SSO integration through the institution's existing Google Workspace or Microsoft 365 directory. First-time setup from infrastructure provisioning to first student login has been benchmarked at under 4 hours for a Tier 1 institution following the documented runbook.

### 9.2. Use Cases Beyond Higher Education

While designed for Indian engineering colleges, CoE-IDMA's architecture is applicable to secondary schools (Grade 9–12 boards), professional

certification training centres, corporate learning and development programmes, and government skill-development initiatives (NSDC, PMKVY). The modular microservices design allows institutions to deploy only the modules relevant to their context — for example, a corporate training centre may enable Course Management, Task Tracker, and Certificate Engine while disabling Gamification and QR Attendance. The AI recommendation engine can be retrained on domain-specific interaction data (e.g., professional certification pathways) without modifying the platform codebase. Multilingual support (currently English; Tamil, Hindi, Telugu planned for v2.0) further broadens addressable deployment contexts across India's linguistically diverse states.

### 9.3. Ethical Considerations and Governance

CoE-IDMA collects GPS location data at attendance events — a privacy-sensitive operation requiring explicit, informed student consent documented through an in-app consent workflow at first launch. Location data is retained only as a binary geofence pass/fail signal; precise coordinates are discarded server-side after validation and are never stored in the attendance database. The AI monitoring system's at-risk flag triggers teacher notification but does not directly penalise students or affect grades — flagged students receive supportive study plans, not disciplinary records. Institutional data governance policies are enforced through configurable data retention periods (default: 3 years, configurable 1–7 years), automated PII anonymisation for research exports, and a FERPA/GDPR-compliant data deletion workflow operable by the institution admin.

## 10. Future Work

### 10.1. Short-Term Roadmap (v2.0 — 12 months)

The immediate development priorities for CoE-IDMA v2.0 are: (1) Live video integration using WebRTC for virtual classroom sessions, enabling synchronous online lectures within the same app without requiring Zoom or Google Meet; (2) Tamil, Hindi, and Telugu UI localisation targeting the three largest student demographics in the current user base; (3) Advanced analytics dashboard for teachers providing cohort-level performance heatmaps, course difficulty calibration metrics, and AI-generated

teaching effectiveness scores; (4) Parent/guardian portal allowing family members of undergraduate students to view attendance summaries and performance alerts with student consent; and (5) iOS push notification reliability improvements targeting >99.5% delivery rate under the current 94.3% baseline.

### 10.2. Medium-Term Research Directions (v3.0 — 24–36 months)

Three research-grade development tracks are planned. First, Federated Learning implementation: replacing the current centralised LSTM model with a privacy-preserving federated architecture trained across participating institutions without sharing raw student data — improving model accuracy through larger effective training sets while complying with institutional data sovereignty requirements. Second, AR/VR Laboratory Simulations: integrating immersive virtual lab environments for engineering disciplines (circuit simulation, chemical reaction visualisation, mechanical assembly) using WebXR-compatible devices, reducing the need for expensive physical lab equipment in resource-constrained colleges. Third, Emotion-Aware AI: integrating non-intrusive sentiment analysis on student chat messages and task submission patterns (keystroke timing, revision frequency) to detect academic anxiety and burnout signals, triggering counsellor referral workflows before students disengage entirely.

### 10.3. Long-Term Vision (v4.0+)

The long-term vision positions CoE-IDMA as the backbone of India's National Digital Campus Infrastructure — a federated network of institutional CoE-IDMA deployments connected to the National Academic Depository (NAD) for permanent credential storage, the Academic Bank of Credits (ABC) for cross-institutional credit transfer, and DigiLocker for student document management. This vision aligns with India's National Education Policy 2020 (NEP 2020) mandate for technology-enabled, outcome-based education with flexible credit pathways. Achieving this vision requires standardising CoE-IDMA's certificate format to the W3C Verifiable Credentials specification, enabling cryptographically verified digital credentials readable by any standards-compliant employer or

institution system globally.

## Conclusion and Future Work

### • Summary of Contributions:

This paper presented CoE-IDMA, an AI-powered cross-platform application that integrates ten critical academic functions — user management, course delivery, attendance, task tracking, communication, AI assistance, gamification, resources, admin analytics, and blockchain certificates — into a single unified mobile-first ecosystem.

### Research Contributions

The architecture contribution: a five-layer microservices design achieving 99.7% uptime with 187ms mean API response under 2,000 concurrent users. The design is replicable across any academic institution deploying cloud-native platforms. The algorithmic contribution: Performance Scoring  $P = \alpha A + \beta T + \gamma Q + \delta E$  provides a quantifiable composite metric, while LSTM anomaly detection (87% precision, 82% recall) enables proactive intervention before academic failure — a significant advance over reactive post-exam approaches. The verification contribution: HMAC-SHA256 QR anti-spoofing reduced proxy attendance from 12.4% to 0.3%. Blockchain certificate generation via Hyperledger Fabric replaced the 3–5 day manual process with 1.8-second automated issuance with immutable on-chain verification.

### Experimental Validation

A 90-day pilot at Paavai Engineering College (450 students, 28 teachers, 5 admins; CSE, ECE, MBA) validated all five key performance indicators at  $p < 0.01$ . Attendance accuracy: 74% → 99.2% (+25.2pp). Task submission: 60% → 94% (+34pp). Engagement index: 100 → 270 (+170%). Certificate generation: 3–5 days → 1.8 seconds. Student satisfaction: 4.3/5.0 on Likert scale (n=450).

### Comparison with Existing Platforms

Benchmarking against Moodle, Canvas, Google Classroom, and Blackboard confirmed CoE-IDMA as the only platform providing all nine evaluated features natively — without expensive third-party plugins — including QR+GPS attendance, AI recommendation, real-time chat, gamification, auto-certificates, offline mode, multi-role dashboards, AI

scoring, and blockchain verification.

### Limitations

AI cold-start accuracy is reduced for users with fewer than 4 weeks of activity history. GPS geofencing requires explicit device location consent. Live video streaming for virtual classes is planned but not yet in the current release.

### Future Work

**Table 12 Future Work**

ID	Future Research Direction
F1	Federated Learning: Cross-institutional model training without sharing raw student data — improving AI accuracy across college networks while preserving privacy.
F2	AR/VR Integration: Immersive laboratory and classroom simulations using Augmented and Virtual Reality for engineering and medical programs.
F3	Facial Recognition: Supplementary biometric attendance to complement QR+GPS, subject to ethical review and informed student consent.
F4	Regional Languages: UI expansion to 12 Indian regional languages — Tamil, Telugu, Kannada, Malayalam, Hindi, Bengali, Marathi, Gujarati, and others.
F5	NAD Integration: Sync with India's National Academic Depository for permanent, government-recognized certificate storage and verification.
F6	Emotion-Aware AI: Sentiment analysis on student interactions to detect early academic stress and trigger counselling support workflows.

In conclusion, CoE-IDMA demonstrates that a holistic, AI-augmented approach — treating communication, monitoring, analysis, and certification as inseparable functions — produces measurable, statistically significant improvements across all dimensions of student and institutional performance. The modular microservices design ensures CoE-IDMA can be adopted and extended by any educational institution regardless of size or

existing infrastructure shown in Table 12.

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