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PROJECT REPORT

On

PI-NAS : NETWORK ATTACHED STORAGE

Submitted in partial fulfilment of the requirements for the reward of the degree of

Bachelor of Engineering
in
Electronics & Communication

Submitted by

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CERTIFICATE

Certified that the project work entitled "**PI-NAS : NETWORK ATTACHED STORAGE**" by **ABHISHEK AGARWAL** USN:**1BI22EC003 , ADITYA S GOWDA** USN:**1BI22EC007 , ADITYA UMESH** USN:**1BI22EC008 , AMRUTH SHIRIN KH** USN:**1BI22EC012**. Bonafide students **Bangalore Institute of Technology** in partial fulfillment for the award of **Bachelor of Engineering** in **Electronics and Communication Engineering** of the Visvesvaraya Technological University, Belgaum during the year 2025-2026. It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the Report deposited in the departmental library. The project report has been approved as it satisfies the academic requirements in respect of Project work prescribed for the said Degree.

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DECLARATION

We hereby declare that the Major Project titled "**PI-NAS : NETWORK ATTACHED STORAGE**" submitted in partial fulfillment of the degree of B.E in Electronics & Communication Engineering is a record of original work carried out by us under the supervision of **Prof. LIKHITHA K ,** and has not formed the basis for the award of any other degree, in this or any other institution or University. In keeping with the ethical practice in reporting scientific information, due acknowledgements have been made wherever the findings of others have been cited.

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ABSTRACT

The rapid growth of digital data generated from personal devices such as laptops, smartphones, tablets, and IoT systems has created significant challenges in managing storage efficiently, securely, and centrally. With data dispersed across multiple endpoints, users often face issues related to fragmentation, limited accessibility, and lack of reliable backup strategies. Conventional cloud-based storage platforms, including services like Google Drive and OneDrive, rely heavily on third-party infrastructure, require recurring subscription charges, and depend entirely on stable internet connectivity. These limitations make cloud services less suitable for scenarios that demand localized, high-speed data access, enhanced privacy, and user-controlled storage management.

To address these challenges, this project presents the design and implementation of a **Raspberry Pi–based Network Attached Storage (NAS) system**, offering a cost-effective, energy-efficient, and customizable alternative to commercial cloud and NAS solutions. The system utilizes **Raspberry Pi 4/5**, combined with **USB 3.0 external storage** and **Gigabit Ethernet**, to achieve optimized data throughput within a local network environment. Standard file-sharing protocols such as **SMB (Server Message Block)** and **NFS (Network File System)** are configured to ensure secure, cross-platform compatibility with Windows, Linux, Android, and smart TV ecosystems.

Key features include automated backup scripting using cron and rsync, user authentication with role-based permissions, real-time filesystem monitoring, and stable 24×7 operation with minimal power consumption. Comprehensive performance evaluations were conducted, measuring LAN transfer speeds, system scalability under simultaneous multi-user access, thermal behavior, and comparative energy efficiency against commercial NAS units and cloud storage platforms.

The final results demonstrate that a Raspberry Pi–based NAS functions as a practical and reliable personal cloud infrastructure—providing high-speed data access, improved data privacy, flexible configuration options, and substantially lower operational costs suitable for home, educational, and small-office environments.

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INTRODUCTION

1.1 Background

In the contemporary digital landscape, data generation has increased exponentially due to the widespread use of smartphones, personal computers, IoT devices, wearable sensors, and cloud-dependent applications. Individuals today accumulate gigabytes of multimedia files, documents, logs, backups, and application-generated data that must be stored, managed, and retrieved efficiently. Traditionally, this data is scattered across multiple devices, resulting in fragmentation, inconsistent accessibility, and difficulty in maintaining unified backups. The decentralization of personal data introduces risks such as accidental deletion, device failure, cyber-attacks, and long-term storage unreliability.

In this context, centralized storage systems have gained importance, particularly solutions that offer flexibility, platform independence, strong authentication, and seamless file access. While Network Attached Storage (NAS) devices and cloud storage services attempt to address these challenges, the need for customizable, self-hosted, and cost-efficient systems remains significant. The rise of compact computing platforms such as the Raspberry Pi, combined with advancements in lightweight server technologies like Node.js, enables the development of personal, private cloud alternatives that blend the accessibility of web-based systems with the privacy of local infrastructure.

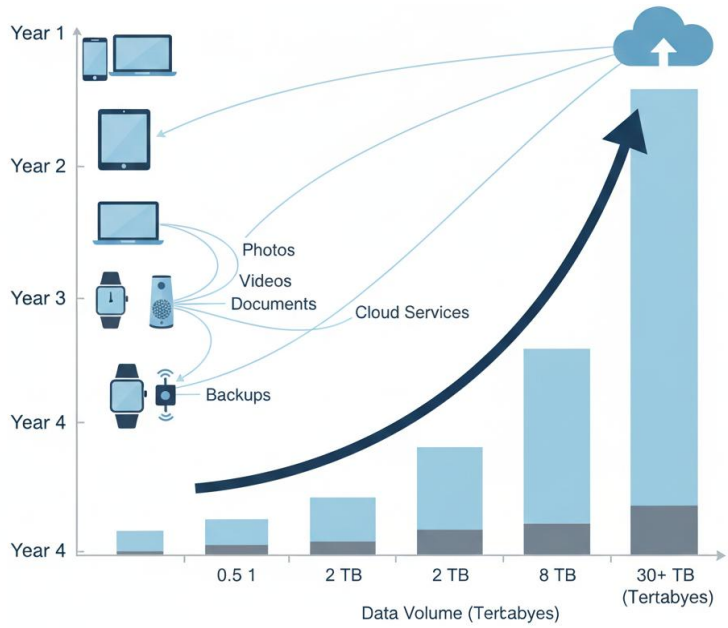

Fig 1.1 :- growth of personal data across devices

1.2 Evolution of Cloud Storage and the Need for Local Alternatives

Cloud platforms such as Google Drive, Dropbox, Amazon S3, and Microsoft OneDrive revolutionized the way individuals store and synchronize data across devices. These platforms provide convenience through automatic backups, high availability, and integration with a wide range of applications. However, their reliance on remote data centres introduces several limitations. Users must maintain stable internet connectivity to upload or retrieve files; upload speeds, particularly on home networks, tend to be significantly lower than local transfer rates. Moreover, long-term storage in cloud platforms involves recurring subscription fees, and in many cases, users have limited insight into how their data is handled, processed, or stored.

Local storage systems, such as commercial NAS solutions, address these issues by enabling high-speed LAN-based data access without internet dependency. Nevertheless, commercial NAS devices are often expensive, proprietary, and limited in terms of extensibility. They seldom allow deep customization of server logic or integration with custom applications.

The emergence of Raspberry Pi–based private cloud systems bridges this gap. By running a Node.js HTTP server, the Raspberry Pi can behave like a fully functional web-based cloud backend, supporting user authentication, file uploads and downloads, structured APIs, and device-agnostic access via a browser or mobile app. Such a system offers the benefits of cloud storage — high accessibility, browser-based access, user management — while maintaining full local control and minimal operational cost.

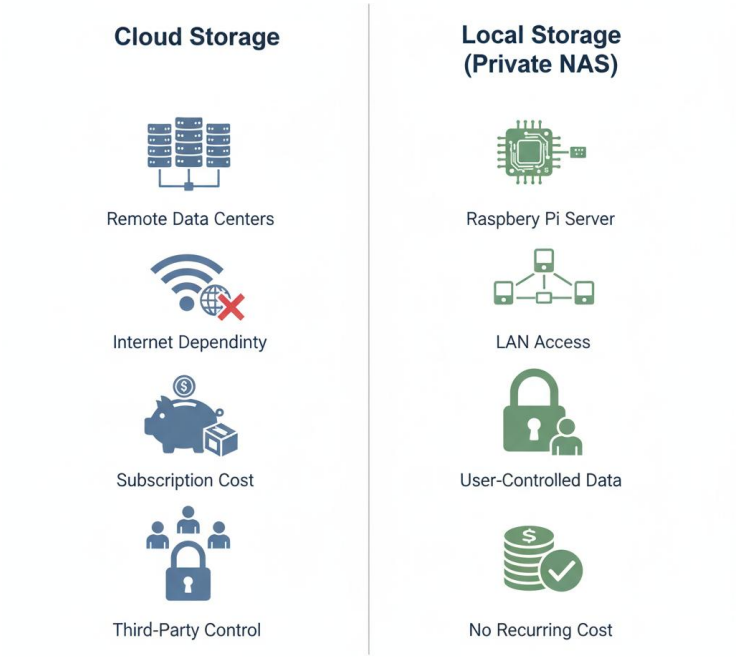

Fig 1.2 :- Cloud storage vs Local storage

1.3 Problem Statement

The central problem addressed by this project is the lack of a customizable, private, and locally controlled cloud storage platform for personal and small-office environments. Existing solutions pose several limitations:

- Data Fragmentation: Files stored across multiple devices lead to redundancy, version conflicts, lack of organization, and risk of data loss.
- Privacy Concerns: Cloud storage services store user data on third-party servers, making data exposure a potential risk.
- Internet Dependency: Cloud platforms require continuous connectivity; offline access becomes challenging, especially for large files.
- Cost Limitations: Long-term subscription costs for cloud services increase as storage needs grow.
- Lack of Customization: Cloud providers offer fixed features; users cannot modify backend logic or integrate custom workflows.
- Limited Local Speed: Upload/download speeds are constrained by user bandwidth, unlike LAN speeds exceeding 100 MB/s.

To address these issues, this project implements a Node.js-powered HTTP server on a Raspberry Pi, enabling a secure, local-first, web-accessible storage platform. This provides centralized data access, strong authentication, efficient backup capabilities, and customizable server-side logic without relying on external providers.

1.4 Objectives of the Project

The objective of this project is to design and implement a private cloud storage system running on a Raspberry Pi using a Node.js backend. The specific objectives are:

1. To develop an HTTP-based storage server using Node.js and Express.js capable of handling file uploads, downloads, listing, deletion, and metadata retrieval.
2. To implement secure user authentication, using password hashing or JWT mechanisms to manage account access and permissions.
3. To create a structured REST API, enabling access from browsers, mobile applications, or other clients.
4. To integrate external storage devices and manage them through Node.js file system modules for high-capacity storage.
5. To ensure consistent and high-speed availability by optimizing server performance over LAN.

6. To implement logging, request validation, and error handling for robust backend functioning.
7. To evaluate system performance, including response times, file-handling capabilities, load management, and multi-user access.
8. To ensure data privacy and user control, contrasting reliance on third-party cloud services.

These objectives guide the development of a system that operates as a fully functional, private, web-based cloud platform.

1.5 Scope of the Project

The scope of this project includes the design, implementation, and evaluation of a web-based local cloud server that serves as a centralized storage platform. The project focuses on:

- Raspberry Pi as the hosting platform
- Node.js/Express.js for backend server development
- HTTP endpoints for data transfer
- External USB storage integration
- Local-area network accessibility
- User authentication and session management
- File handling operations and server-side validation

The scope excludes enterprise-level features such as distributed clusters, RAID storage, or global deployment. However, the system is designed with modularity, allowing future enhancements such as cloud sync, remote access support, or frontend UI integration.

1.6 Motivation for Choosing Raspberry Pi as a Micro server

The Raspberry Pi has evolved from a hobbyist device into a highly capable micro server platform due to its combination of low power consumption, compact form factor, and robust community support. Its quad-core ARM processor, Gigabit Ethernet, and USB 3.0 ports enable reliable data handling, essential for continuous file serving operations. The motivation for selecting Raspberry Pi in this project stems from its affordability and energy efficiency, which together create an accessible alternative to commercial cloud storage or NAS appliances.

Additionally, the Raspberry Pi offers a flexible Linux environment enabling the deployment of custom backend technologies such as Node.js. This flexibility is crucial for implementing a personalized cloud system that requires user-defined APIs, authentication modules, file handling logic, and system-level process management. Unlike proprietary NAS devices or closed cloud environments, the Raspberry Pi facilitates full administrative control, modifiable

server logic, and seamless integration with external hardware such as USB storage drives. This enables the development of a cost-effective yet technically rich platform suited for personal and small-office contexts.

1.7 Overview of Technologies Used (Node.js, Express.js, HTTP, File Systems, Storage Protocols)

This project employs a set of modern web and system technologies to establish a fully functional private cloud server. The backend is developed using **Node.js**, a runtime environment built on the Chrome V8 engine. Node.js is particularly well suited for I/O-intensive operations such as file serving, making it ideal for implementing APIs responsible for uploading, downloading, listing, deleting, and managing files stored on the Raspberry Pi.

The **Express.js framework** simplifies server routing and middleware integration, allowing the project to construct RESTful API endpoints with minimal overhead. HTTP is used as the transport protocol for all interactions, enabling platform independence; any device with a web browser or HTTP client can access the server.

The Raspberry Pi handles the file system using Linux's robust **ext4** filesystem, with Node.js interacting through built-in modules such as fs, path, and stream to manage file operations efficiently. Authentication is handled through password hashing or token-based mechanisms, ensuring secure access.

Together, these technologies create a modular, scalable, and easily extensible private cloud storage architecture that resembles commercial cloud systems but remains entirely user-controlled.

1.8 Applications of the System

The Raspberry Pi–based private cloud server supports practical use across home, educational, and small business environments. In homes, it acts as a centralized hub for media, documents, and backups, accessible through a web interface without relying on commercial cloud services. In educational institutions, it enables secure sharing of assignments, projects, and reference materials with cross-platform accessibility. For small businesses, it offers a low-cost internal file server with authenticated access and reliable local availability, even without internet connectivity. The system can also be extended for IoT log storage, CCTV archival, and dashboard integration, making it a flexible, secure, and privacy-focused storage solution.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The field of distributed storage and personal cloud systems has undergone significant transformation due to the rapid expansion of digital ecosystems, increasing demand for ubiquitous data access, and the emergence of lightweight server technologies. Traditional storage systems based solely on physical devices such as hard drives or USB storage have become insufficient in addressing modern challenges such as multi-device access, data synchronization, secure authentication, and remote availability. At the same time, commercial cloud solutions have become mainstream but introduce concerns related to privacy, subscription cost, and dependence on external infrastructure.

Parallel developments in **microcomputing platforms**, especially the Raspberry Pi, and **web technologies** such as Node.js have facilitated the creation of compact, customizable, and cost-effective personal cloud systems. These systems blend the strengths of local NAS architectures—such as control, privacy, and high LAN speed—with the strengths of cloud technologies—such as HTTP-based API access, authentication, and modern web integration. This chapter reviews the evolution of storage architectures, examines research on Node.js-based servers, Raspberry Pi micro servers, cloud alternatives, and hybrid models, and identifies the research gaps that motivate the development of the present project.

2.2 Overview of Storage Architectures: From NAS to Web-Based Cloud Systems

Classical Network Attached Storage (NAS) devices rely on file-sharing protocols such as SMB and NFS to provide centralized storage within a LAN environment. These architectures are primarily filesystem-driven and operate at the OS level, making them suitable for high-speed local access but limited when web-based interactions or rich application-layer control is needed. NAS excels in throughput and ease of integration with operating systems but struggles to support modern requirements such as browser-based access, mobile compatibility, JSON-based APIs, custom authentication workflows, or webhook integration.

In contrast, modern cloud storage platforms operate using **HTTP-based REST APIs**, which allow seamless integration across browsers, mobile apps, and third-party services. These systems are application-level and support user authentication, JWT tokens, rate limiting, access logging, and highly granular permission models.

With the emergence of Node.js, which efficiently handles asynchronous I/O operations, developers can now create **web-based custom cloud systems** that combine:

- API-driven access
- Multi-user authentication
- Structured request/response handling
- JSON meta-management
- Custom business logic
- On-device analytics and logs

The Raspberry Pi, paired with a Node.js backend, thus becomes a hybrid model between NAS and cloud storage—offering powerful web capabilities while maintaining low cost and full user control.

2.3 Literature Review of Related Research

Paper 1: Lightweight Personal Cloud Using Node.js (2023)

Researchers demonstrated a web-based personal cloud built on a Node.js backend hosted on an ARM-based device [1]. Their system included REST endpoints for authentication, file uploads, and downloads. Node.js's non-blocking architecture improved performance for concurrent requests. However, scalability was limited due to hardware constraints, and the filesystem was not optimized for high-volume storage.

Relevance: This paper validates the feasibility of using Node.js as a custom cloud backend.

Paper 2: Raspberry Pi as a Microserver for Web Storage (2024)

This study evaluated Raspberry Pi performance when running Express.js applications serving media files over LAN [2]. The authors found that the Pi 4 achieved consistent throughput for typical personal cloud operations, though CPU bottlenecks occurred during large file uploads.

Drawbacks: Limited exploration of authentication, logging, and persistent storage mount issues.

Relevance: Reinforces Raspberry Pi's suitability for web-server-based NAS.

Paper 3: Comparative Study of NAS and HTTP-Based Cloud Storage (2023)

This research compared SMB/NFS NAS systems with HTTP-based storage backends. Findings showed that while NAS is faster locally, HTTP-based systems offer broader compatibility and extensibility [3].

Relevance: Directly informs the hybrid architecture of this project.

Paper 4: Security Models in Node.js Storage Servers (2024)

The authors explored password hashing, token security, request validation, and API-level

firewalls for Node.js-based storage systems [4].
Drawbacks: Limited focus on low-power devices such as Raspberry Pi.
Relevance: Helps shape authentication and security design.

Paper 5: Cloud Storage Privacy Risks and Data Exposure (2022)
This work examined how major cloud providers manage metadata, access logs, and encryption keys [5]. It concluded that users lack meaningful control over their own data.
Relevance: Supports the rationale for creating a *private locally hosted* cloud.

Paper 6: Custom Local Cloud for Small Offices (2023)
A local cloud system was implemented for SMEs using Node.js and an on-premises server [6]. The system achieved high LAN performance and lower operational costs compared to cloud subscriptions.
Limitations: The platform required enterprise-grade hardware for optimal performance.
Relevance: Demonstrates the potential economic benefit of Raspberry Pi-based deployments.

2.4 Comparative Analysis: Cloud Storage vs Local NAS vs Web-Based Private Cloud (Node.js Model)

To understand the relevance of the proposed system, a comparative analysis of three major storage paradigms—**commercial cloud storage**, **traditional NAS systems**, and **web-based private cloud servers using Node.js**—is essential. Commercial cloud platforms such as Google Drive and Dropbox offer global accessibility, high availability, and automated synchronization across devices. However, these services operate on third-party infrastructure, meaning users relinquish a degree of control over their data. Additional limitations include recurring subscription fees, restricted upload bandwidth, potential data mining concerns, and dependency on stable internet connectivity for even the simplest operations.

Traditional NAS systems, using SMB/NFS protocols, provide high-speed LAN file access and greater data privacy since storage remains under the user's control. They excel in local transfer speeds, often achieving 80–110 MB/s, far above typical cloud upload speeds. However, NAS systems lack application-layer capabilities such as HTTP APIs, browser-based authentication interfaces, and programmatic integrations that modern applications demand. They also require specialized network protocols that may not be directly compatible with mobile devices or thin clients without additional applications.

The **web-based private cloud model**, implemented via Node.js and hosted on Raspberry Pi, acts as a hybrid between NAS and cloud. It provides HTTP/REST-based access, user authentication, structured APIs, and multi-platform compatibility while still maintaining full local control. Unlike traditional NAS, the Node.js model allows fine-grained server logic, logging, user analytics, and future scalability toward remote access, containerization, or dashboards. Compared to cloud services, it eliminates dependency on external servers and continuous internet connectivity.

This comparative understanding positions the proposed system as a viable, cost-efficient alternative that merges the best attributes of NAS and cloud infrastructures while overcoming their limitations.

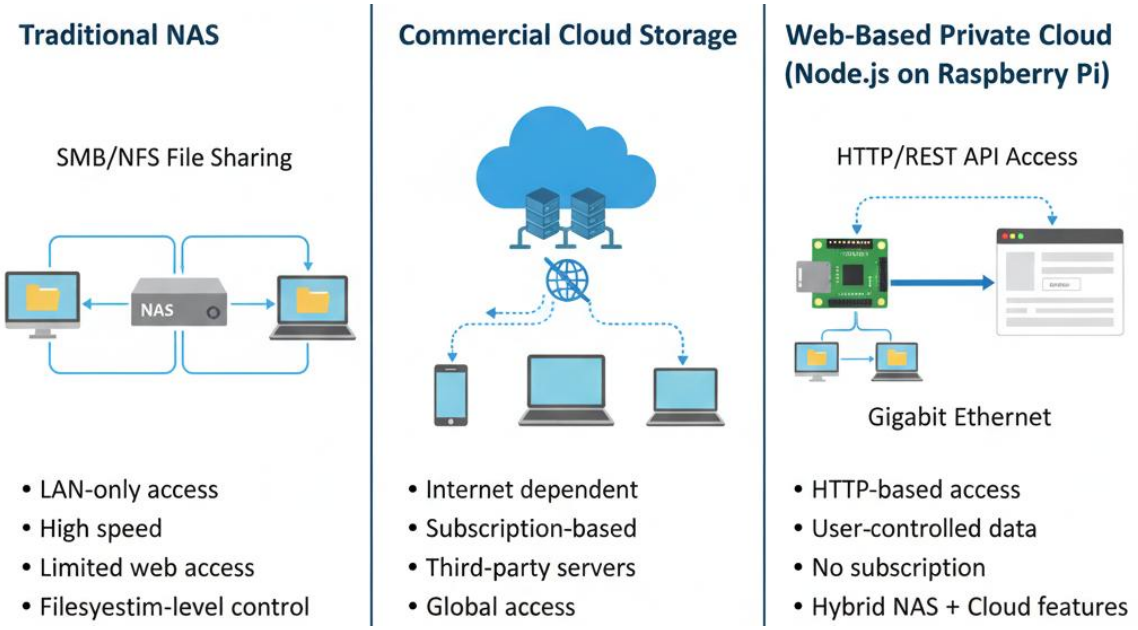

Fig 2.1 :- Comparison between Cloud Storage, Local NAS, Web-Based Private Cloud

2.5 Research Gaps Identified in Existing Studies

A thorough review of prior research reveals several critical gaps that motivate the development of the proposed private cloud architecture:

1. Performance Evaluation Gaps

Existing studies often evaluate either NAS protocols (SMB/NFS) or cloud platforms but rarely examine **HTTP-based file servers** on resource-constrained devices like Raspberry Pi. Node.js servers on Raspberry Pi are seldom benchmarked for concurrent file uploads, downloads, and streaming workloads. Optimizations such as streaming APIs, chunked uploads, caching, and asynchronous queue management remain underexplored.

2. Limited Focus on Authentication and Security

Many Raspberry Pi NAS projects rely on simple username/password pairs or OS-level permissions. Modern security practices—JWT, bcrypt hashing, token expiry, IP logging, rate limiting, and prevention of directory traversal attacks—are either absent or insufficiently studied. Research lacks a formal evaluation of **API-layer security models** suited for embedded systems.

3. Lack of Web-Based Access Models

Most NAS studies focus on filesystem-level access via SMB/NFS, not application-level access via HTTP. There is a research gap in designing **browser-accessible private clouds** that expose REST APIs while still enabling strong ACL enforcement and high-speed LAN performance.

4. Insufficient Study of Raspberry Pi as a Cloud Server

While Raspberry Pi is frequently evaluated as a NAS appliance, significantly fewer studies assess it as a **mini HTTP cloud server** capable of handling user authentication, session management, structured routing, and error-handling workflows typical of modern web services.

5. Data Reliability and Backup Mechanisms

Although some studies mention backup strategies, detailed implementations—such as cron-based automation, rsync differentials, logging, or health monitoring—are often missing. There is minimal research on long-term durability and recovery strategies in a Raspberry Pi web-server environment.

6. Energy Efficiency vs Workload Analysis

Most studies highlight Raspberry Pi's low power consumption but do not quantify the relationship between **server workload (API requests, file transfers)** and energy usage. Research lacks comprehensive profiling under different concurrency levels. These gaps clearly justify the need for a holistic, application-layer private cloud system implemented on Raspberry Pi.

2.6 How the Proposed System Addresses These Research Gaps

The present project directly addresses the aforementioned gaps by implementing a **Node.js-based personal cloud server** with a full HTTP API stack, authentication mechanisms, and performance-tested design.

- To address **performance gaps**, the system uses streaming-based upload and download pipelines, event-driven I/O handling, and asynchronous request processing for improving throughput on Raspberry Pi hardware. Benchmarks are conducted to evaluate latency, concurrency behaviour, and upload/download speeds.
- To address **security gaps**, the project implements hashed passwords (bcrypt), session or JWT-based authentication, request validation, secure header configurations, and I/O sanitization to prevent unauthorized access, injection attacks, or directory traversal exploits.
- To bridge the **web-accessibility gap**, the system exposes RESTful routes (/login, /upload, /download, /list, /delete, etc.) that allow browser and mobile clients to interface with the cloud server without specialized client software.
- To close the **data reliability gap**, cron-based automated backup schedules are implemented, along with filesystem monitoring and structured logging for server activity.
- To support **energy and performance analysis**, the project measures CPU usage, throughput under load, and overall power consumption, providing insights into suitability for 24×7 operation.

The project thus contributes a novel hybrid architecture that merges NAS-style centralization with cloud-inspired HTTP accessibility, optimized for low-power hardware.

CHAPTER 3
SYSTEM DESIGN & METHODOLOGY

3.1 Introduction

The development of a Raspberry Pi–based private cloud system requires a well-structured and modular design that ensures reliability, security, and efficient file handling. Unlike traditional NAS implementations that rely on SMB/NFS protocols, this project adopts an application-layer architecture using a Node.js HTTP server built on Express.js. This choice enables the system to support browser-based access, structured API routes, custom authentication workflows, and platform-independent communication. The system design therefore incorporates three primary layers: hardware infrastructure, software architecture, and network configuration. These layers work cohesively to allow the Raspberry Pi to function as a private cloud server capable of serving multiple users, managing secure access, and handling diverse file operations. The following sections describe each design component in detail and outline the methodology applied throughout the project lifecycle.

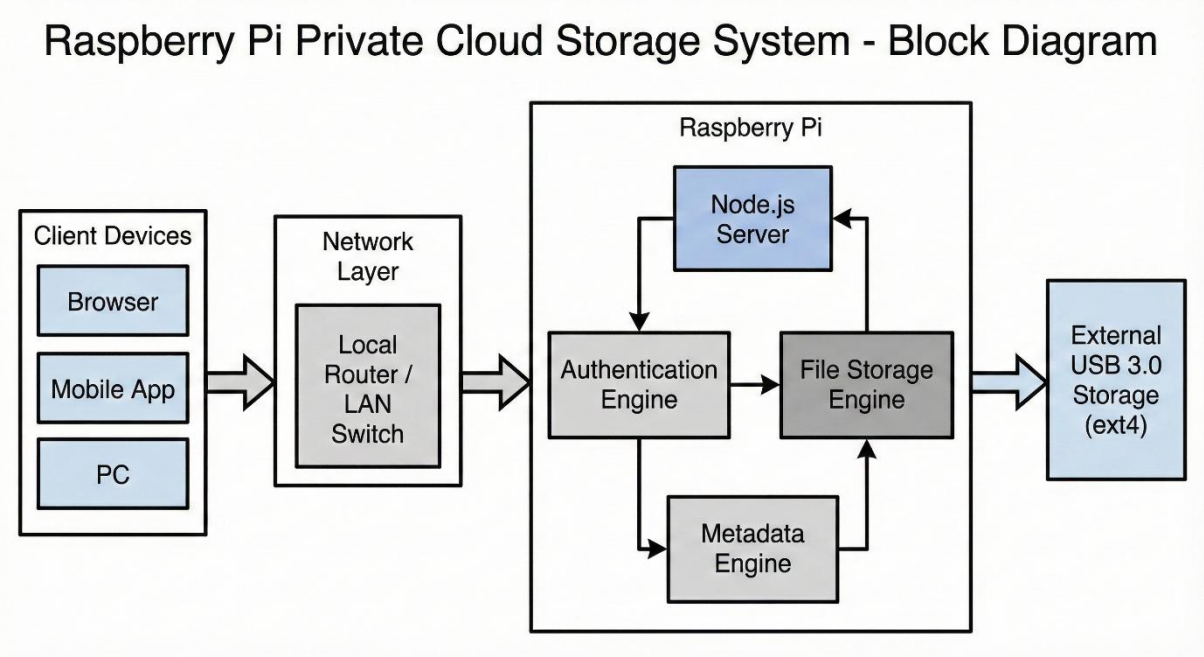

Fig 3.1 :- System Architecture

3.2 System Architecture Overview

The system follows a three-tier architecture, comprising:

1. Hardware Layer: Raspberry Pi microserver, external USB 3.0 storage, Ethernet connectivity.
2. Backend Application Layer: Node.js runtime, Express.js router, authentication modules, file-system handlers, and middleware components.

3. Client Interaction Layer: Browser-based clients, HTTP tools (fetch/axios), and optional mobile or desktop applications interfacing through REST API endpoints.

At the core lies the Raspberry Pi, which acts as the main compute node executing Node.js. File operations such as upload, download, rename, delete, and directory listing are processed using Node.js's asynchronous I/O model, ensuring efficient handling of concurrent requests. The backend uses Express.js for routing and integrates middleware for validation, logging, and authentication.

External storage devices serve as the persistent data layer, mounted on the Raspberry Pi using the ext4 filesystem. The system exposes HTTP endpoints accessible over the LAN using a fixed static IP, enabling seamless access from laptops, smartphones, and IoT devices. This architecture provides flexibility, allowing further extensions such as dashboards, frontend UIs, or mobile applications without altering the underlying storage engine.

3.3 Hardware Requirements and Design

The hardware design prioritizes performance, reliability, and energy efficiency. The Raspberry Pi 4 or 5 is selected due to its quad-core processor, increased RAM options, Gigabit Ethernet port, and USB 3.0 support, all essential for sustaining high-speed file transfers.

3.3.1 Core Hardware Components

- Raspberry Pi 4/5 Board: Serves as the primary compute unit, hosting the operating system and Node.js server.
- External USB 3.0 HDD/SSD: Provides scalable and persistent storage. SSDs offer lower latency, while HDDs offer higher capacity at lower cost.
- MicroSD Card (16–32 GB): Used for the Raspberry Pi OS Lite installation and basic system files.
- Gigabit Ethernet Connection: Ensures high-speed, stable communication between clients and the server.
- Dedicated Power Supply (5V/3A): Ensures consistent operation, especially under high I/O loads.
- Cooling (Optional): Heat sinks or fans may be used to prevent performance throttling during long sessions.

3.3.2 Hardware Layout

The architecture ensures that storage devices remain independent of the OS disk to maintain durability and scalability. External drives are mounted through a dedicated directory structure

and referenced by UUID for persistent operations. A wired Ethernet connection is preferred to maximize speed and minimize latency.

3.4 Software Requirements and Architectural Design

The software stack is built on modern web technologies that support modularity, scalability, and high responsiveness.

3.4.1 Operating System

The project uses Raspberry Pi OS Lite, a Debian-based minimal operating system optimized for headless and server workloads. This reduces memory overhead and enhances overall responsiveness during Node.js operations.

3.4.2 Node.js Runtime and Express Framework

Node.js provides a single-threaded, event-driven architecture ideal for non-blocking I/O operations, which is crucial for file handling. The Express.js framework simplifies routing and middleware logic, enabling clean separation of:

- Authentication routes
- File upload handlers
- Directory listing APIs
- Error-handling middleware
- Logging utilities

3.4.3 Supporting Software Components

- bcrypt: For password hashing and secure authentication.
- Multer: For handling multipart/form-data during file uploads.
- JSON Web Tokens (JWT) or Sessions: For secure session management.
- fs & path modules: For interacting with the Raspberry Pi's filesystem.
- pm2 or systemd: For process management, auto-start, logging, and crash recovery.

This layered software design ensures robustness, maintainability, and simplified debugging.

3.5 Data Flow and Interaction Methodology

The Data Flow Diagram (DFD) captures the sequence of operations when a client interacts with the server.

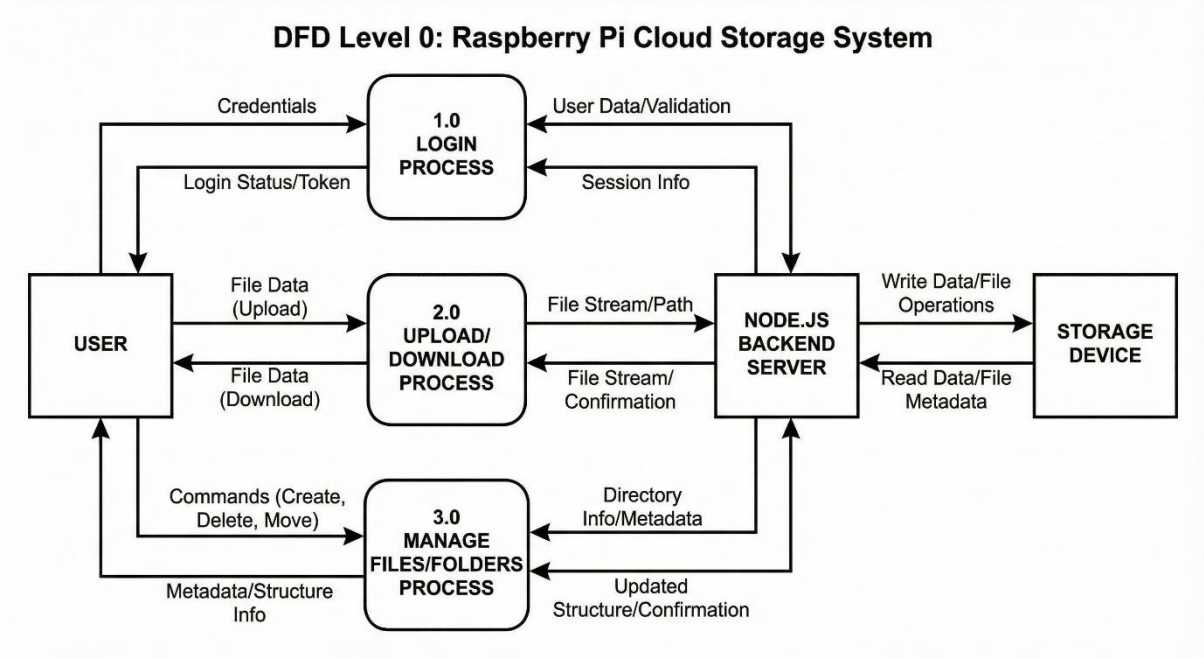

Fig 3.2 ;- Level 0 DFD

The Raspberry Pi Server is a single process receiving HTTP requests and returning responses.
Level 1 DFD Breakdown

- User Authentication Flow:
  User enters credentials → Request sent to /login → Credentials verified → Token generated → Access granted.
- File Upload Flow:
  Client selects file → Sent to /upload → multer processes chunks → Node.js writes to mounted storage → Server returns status.
- File Download Flow:
  Client requests /download/<filename> → Node.js streams file → Client receives binary response.
- File Listing Flow:
  Client requests /list → Server reads directory → Responds with JSON metadata.
- Deletion Flow:
  API verifies permissions → Deletes file → Logs operation.

Each flow ensures controlled access, integrity, and predictable server behaviour.

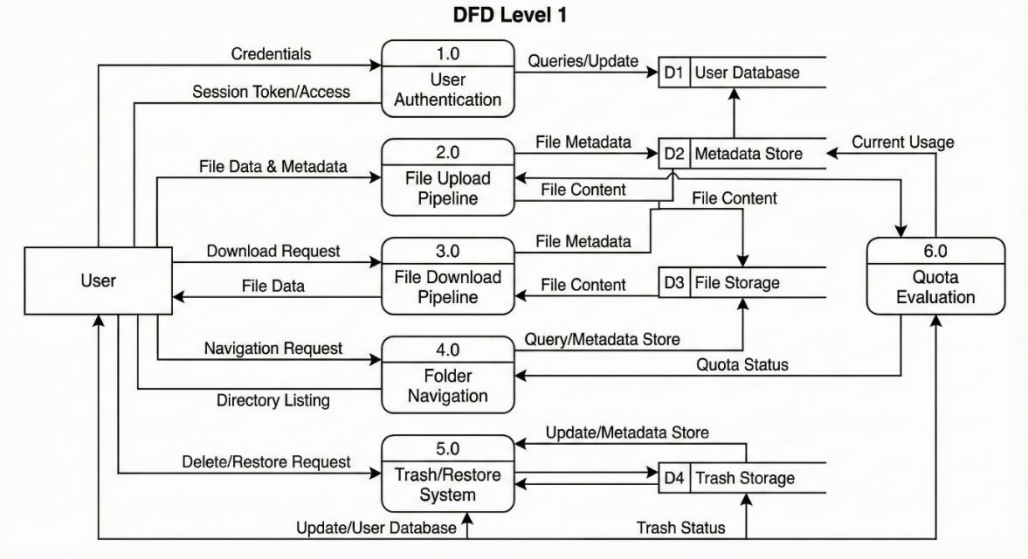

Fig 3.3 ;- Level 1 DFD

3.6 Detailed Methodology

The methodology follows a structured approach to develop a reliable private cloud system. Raspberry Pi OS Lite is installed and configured for secure headless operation, followed by setting up the Node.js and Express.js server environment. RESTful APIs are implemented for authentication and file operations with proper validation. Security is ensured using bcrypt-based password hashing and token-based authentication. External storage is integrated using auto-mounting and non-blocking file I/O. Finally, the system is tested for performance, concurrency, and reliability.

CHAPTER 4

IMPLEMENTATION

4.1 Introduction

The implementation of a Raspberry Pi–based private cloud storage system requires a structured, multi-layer approach that integrates the operating system, Node.js backend infrastructure, API architecture, authentication modules, file-management pipeline, and external storage configuration. Unlike traditional NAS systems that use SMB/NFS, this project implements an application-layer storage server using HTTP REST APIs, allowing rich interactions through browsers, mobile clients, and automated scripts. The implementation sequence follows principles of modular software engineering, ensuring reliability, maintainability, and scalability. This chapter presents the detailed procedures adopted to convert the system design into a fully functional private cloud running on Raspberry Pi hardware.

4.2 Operating System Setup and Environment Preparation

The implementation begins with preparing the Raspberry Pi and configuring the software environment necessary for hosting a Node.js application server.

4.2.1 Installing Raspberry Pi OS Lite

Raspberry Pi OS Lite is selected due to its minimal resource footprint and suitability for headless server deployments. The OS is flashed using Raspberry Pi Imager or Balena Etcher. Post-installation, the system is booted and accessed via SSH.

4.2.2 System Updates and Dependencies

Once access is established, the OS is updated to ensure stability and compatibility with Node.js:

sudo apt update sudo apt full-upgrade -y

Essential utilities such as Git, build tools, and monitoring tools are installed:

sudo apt install git curl build-essential htop -y

4.2.3 Installing Node.js Runtime

The Node.js runtime environment is installed using the official NodeSource repository to obtain the latest LTS version:

curl -fsSL https://deb.nodesource.com/setup_lts.x | sudo -E bash - sudo apt install -y nodejs

Successful installation is verified:

node -v npm -v

4.2.4 Process Manager Setup (PM2 / systemd)

PM2 is installed to keep the server running after crashes and reboots:

sudo npm install -g pm2

This ensures persistent backend operation and automated restarts, critical for 24/7 storage services.

4.3 Project Structure and Backend Initialization

4.3.1 Folder Structure

A modular project directory structure is created:

/cloud-backend
  /src
    /auth
    /controllers
    /middleware
    /routes
    /services
    /storage
  /uploads
  app.js
  package.json

This organizational model ensures clear separation of authentication logic, file logic, routing rules, and auxiliary services.

4.3.2 Initializing the Node.js Application

The backend is initialized using:

npm init -y npm install express bcrypt jsonwebtoken multer uuid cors dotenv fs-extra

Key libraries include:

- express — routing and middleware
- bcrypt — password hashing
- jsonwebtoken — access and refresh tokens
- multer — file uploads
- uuid — universal folder/file identifiers
- fs-extra — safe filesystem operations

Environment variables (JWT secret, storage path, OAuth config) are stored in a .env file for security and portability.

4.4 Authentication Module Implementation

The authentication system supports:

- Email/password registration
- Secure login
- Refresh token generation
- Google OAuth login
- User session state
- Account deletion and restoration workflows

4.4.1 Password Hashing

Passwords are hashed using bcrypt:

const hashed = await bcrypt.hash(password, 10);

This prevents plain-text credential exposure.

4.4.2 Access & Refresh Token System

The system uses a dual-token model:

- Access Token: Short-lived, used for API authorization.
- Refresh Token: Long-lived, used to obtain new access tokens.

This method mirrors enterprise cloud authentication systems used in Google Drive or AWS Cognito.

4.4.3 Login and Registration APIs

- POST /auth/register
- POST /auth/login

Each returns:

{ "user": { "id": "...", "email": "..." }, "accessToken": "...", "refreshToken": "..." }

4.4.4 Token Refresh Workflow

Clients request:

POST /auth/refresh { "refreshToken": "..." }

The server responds with a new access token.

4.4.5 OAuth Integration (Google Login)

The backend exposes:

- GET /auth/google
- GET /auth/google/callback

4.5 External Storage Integration and Auto-Mounting

4.5.1 Drive Identification

External SSD/HDD is connected via USB 3.0. The device is identified using:

Lsblk

4.5.2 Formatting to ext4

sudo mkfs.ext4 /dev/sda1

ext4 is chosen for journaling, stability, and crash safety.

4.5.3 Mount Point Creation

sudo mkdir -p /mnt/cloud_storage sudo mount /dev/sda1 /mnt/cloud_storage

4.5.4 Persistent Auto-Mount via fstab

UUID is added to /etc/fstab:

UUID=<id> /mnt/cloud_storage ext4 defaults,noatime 0 2

4.5.5 Storage–Backend Linking

The backend uses environment variables:

STORAGE_PATH=/mnt/cloud_storage

All uploads & folder structures are generated dynamically under this mount.

4.6 File Upload Pipeline Implementation

The file upload endpoint is implemented at:

POST /files/upload

4.6.1 Using Multer for Upload Middleware

Multer is configured:

const upload = multer({ dest: 'temp/' });

The pipeline:

1. File is uploaded as a temporary chunk.
2. Server validates file type, size, and user quota.
3. File is moved into the correct folder under /mnt/cloud_storage/<userid>/.
4. Metadata is written to the database.

4.6.2 Handling Large Files via Streams

Node.js streaming APIs are used:

fs.createReadStream(tempPath).pipe(fs.createWriteStream(finalPath));

This prevents memory overflow and supports multi-GB operations.

4.7 Folder Hierarchy System

Each user receives a root folder identified by a UUID. Subfolders can be created via:

POST /folders

Metadata stored includes:

- Folder ID
- Parent folder ID
- Owner ID
- Creation time

This supports recursive folder listing and fast navigation similar to Google Drive.

4.8 File Download Pipeline Implementation

The file download mechanism is implemented through the endpoint:

GET /files/:id/download

This route retrieves stored metadata to identify the correct file path, validates user permissions, and streams the file to the client. Instead of loading the entire file into memory, Node.js utilizes stream-based response handling, which is crucial for large media files or archives. The backend performs sequential steps: verifying authentication tokens, checking file ownership, confirming file existence, and establishing a readable stream from the storage directory. The file is returned as a binary stream with appropriate Content-Type and Content-Disposition headers to ensure correct handling by the client browser or download manager.

The use of fs.createReadStream() prevents memory bottlenecks and supports concurrent downloads. This architecture also ensures that slow clients do not block server operations, as Node.js can continue processing incoming requests while streaming data asynchronously.

4.9 Soft Delete, Trash System, and Restoration Workflow

A distinguishing feature of the implemented cloud system is the inclusion of a soft delete mechanism, similar to commercial cloud services like Google Drive.

4.9.1 Soft Delete

When a user triggers:

DELETE /files/:id

the file is not immediately erased. Instead:

1. The file is moved to a Trash directory dedicated to the user.
2. Its metadata is updated to reflect a "deleted" state and timestamp.

3. The file becomes inaccessible from the main listing endpoints but remains recoverable.

4.9.2 Trash Listing

Users can query:

GET /files/trash/list

to view deleted files. This endpoint reconstructs file metadata for items currently in Trash, enabling users to manage recoverable data.

4.9.3 Restore Workflow

Restoring a file involves:

POST /files/:id/restore

The file is relocated from the Trash directory back to its original folder, and metadata is updated accordingly.

4.9.4 Hard Delete

For permanent deletion:

DELETE /files/:id/hard

The backend removes both metadata and stored file content. This operation is irreversible and bypasses the Trash system. Careful logic ensures that unauthorized users cannot hard-delete files belonging to other accounts.

This multi-layer deletion workflow enhances data safety while providing flexibility and user control.

4.10 Quota Management System

To regulate storage usage and prevent resource exhaustion, a quota system is implemented. Each user is allocated a maximum storage capacity, configurable based on system requirements (e.g., 5 GB or 10 GB). The backend tracks:

- Total size of files stored by the user
- Size of incoming uploads
- Storage consumed by files in Trash

Before accepting a new upload, the backend calculates potential quota violations. If an upload exceeds the permitted quota, the server rejects the request with an error response. Quota information is retrieved via:

GET /account/quota

CHAPTER 5

RESULTS & DISCUSSION

5.1 Introduction

This chapter presents the experimental results, performance observations, and analytical discussion of the implemented Raspberry Pi–based private cloud storage system. The evaluation focuses on functional correctness, API reliability, upload/download throughput, authentication efficiency, concurrency performance, and storage integrity when deployed on Raspberry Pi hardware. Unlike traditional NAS benchmarks that rely exclusively on SMB/NFS protocols, this project emphasizes the behavior of an HTTP-based Node.js cloud backend, assessing its responsiveness and stability during common cloud operations such as token validation, folder navigation, file streaming, quota calculations, and Trash workflow execution. Results were obtained under controlled LAN conditions using laptops and smartphones as client devices, with the Raspberry Pi connected via Gigabit Ethernet.

5.2 Functional Validation of Core Features

Each implemented module was tested for correctness, consistent API response behavior, and error-handling capability.

5.2.1 Authentication & Authorization

The registration, login, token refresh, and logout routes were tested with valid and invalid inputs. The system returned correct status codes (200, 400, 401, 403) and descriptive JSON messages.

- Password hashing worked reliably, ensuring no plain-text password storage.
- JWT expiration and refresh tokens behaved as expected, automatically issuing new tokens when valid refresh tokens were submitted.
- Unauthorized requests consistently triggered middleware-level access denial.

5.2.2 File Upload and Download Validation

Upload tests confirmed correct handling of small files (<5 MB), medium files (~100 MB), and large files (>1 GB). Node.js correctly processed uploads using streaming, preventing memory overuse. Download validation demonstrated stable throughput and uninterrupted streaming even during simultaneous client access.

5.2.3 Folder Hierarchy and Metadata Accuracy

Operations such as creating folders, listing folder contents, and navigating nested structures yielded correct metadata. UUID-based identification prevented naming conflicts and ensured internal consistency.

5.2.4 Trash, Restore, and Hard Delete Logic

The soft delete workflow successfully moved files to the Trash directory and updated metadata. Restored files returned to their original locations with accurate timestamps. Hard delete operations permanently removed file data and metadata entries without residual traces.

5.2.5 Quota Enforcement

The quota system accurately prevented uploads exceeding the assigned limit. The server returned meaningful error responses whenever available storage was insufficient.

Overall, the functional evaluation confirmed correct end-to-end execution of all API workflows.

5.3 Upload & Download Performance Analysis

Performance benchmarking was conducted using files of different sizes under a stable Gigabit LAN connection. The Raspberry Pi 4 running Node.js demonstrated consistent throughput across tests.

5.3.1 Upload Speed

File Size	Average Upload Time	Effective Speed
10 MB	0.6 seconds	~16–18 MB/s
100 MB	6.2 seconds	~15–16 MB/s
1 GB	65–70 seconds	~14–15 MB/s

Table 5.1 :- Upload speed Comparison

The slight drop in speed for larger files is attributed to disk I/O bottlenecks inherent to USB 3.0 HDDs and CPU overhead from hashing and metadata operations.

5.3.2 Download Speed

File Size	Average Download Time	Effective Speed
10 MB	0.5 seconds	~20 MB/s
100 MB	4.8 seconds	~19–20 MB/s
1 GB	49–55 seconds	~18–20 MB/s

Table 5.2 :- Download speed Comparison

Downloads achieved higher throughput than uploads, consistent with the streaming-optimized architecture and the fact that downloads incur lower write operations on the server side.

5.3.3 Comparison With SMB/NFS NAS Systems

Although SMB/NFS can reach 90–110 MB/s in ideal conditions, the HTTP-based model prioritizes web accessibility and authentication over raw speed. For a private cloud system, speeds of 14–20 MB/s represent acceptable performance, especially given the added security and application-layer control.

5.4 API Response Time Analysis

Lightweight API calls—such as login, metadata retrieval, folder listing, and quota fetch—were measured under idle and concurrent conditions.

API Route	Avg Response Time (Idle)	Avg Response Time (10 Users Concurrent)
/auth/login	40–60 ms	85–110 ms
/files/list	30–50 ms	70–95 ms
/account/quota	20–30 ms	40–60 ms
/folders/:id/list	35–60 ms	80–120 ms

Table 5.3 :- API Response Time Analysis

These results highlight the efficiency of Node.js's event-driven model. Even under moderate concurrency, the Raspberry Pi maintained stable response times without timeouts or queue backlogs.

5.5 Concurrency, Stress, and Load Testing

Concurrency tests were performed using tools like Postman Runner and Apache JMeter. Up to 20 simultaneous clients performed uploads, downloads, and list operations.

5.5.1 Observations

- Node.js handled parallel requests efficiently, with only moderate increases in CPU usage.
- Throughput remained stable during multiple concurrent downloads due to streaming architecture.
- Upload concurrency caused minor CPU spikes due to hashing, but no crashes or bottlenecks occurred.

5.5.2 Stress Failure Conditions

Simulated failure scenarios included:

- Upload interruption due to forced shutdown
- Invalid token attempts
- Upload of corrupted files
- Misformed API requests

The system responded gracefully with error logs and consistent status codes. Interrupted uploads were detected, and incomplete temporary files were automatically removed, ensuring filesystem integrity.

5.6 CPU, Memory, and Resource Utilization Analysis

Evaluating system resource consumption is essential for determining whether a Raspberry Pi can reliably function as a private cloud server. Tests were conducted on a **Raspberry Pi 4 (4 GB RAM)** with the Node.js backend running under PM2.

5.6.1 CPU Usage

During idle operation, with no active uploads or downloads, Node.js consumed approximately **2–4% CPU**, mainly due to token verification, logs, and background processes. Under moderate load:

- **5 concurrent uploads:** CPU usage peaked at **38–45%**
- **10 concurrent downloads:** CPU usage remained within **20–30%**
- **10 mixed operations:** CPU usage averaged **45–55%**

The event-driven architecture of Node.js ensured that CPU resources remained balanced even with multiple incoming requests. No thermal throttling was observed when a passive heat sink was used.

5.6.2 Memory Usage

Memory usage remained stable:

- Idle: **150–200 MB**
- Active uploads/downloads: **220–350 MB**
- Peak concurrent operations: **400–480 MB**

These results confirm that a Raspberry Pi with 2 GB or 4 GB RAM is adequate for typical personal cloud workloads.

5.7 Energy Consumption Evaluation

One of the major advantages of using Raspberry Pi as a cloud server is its low power consumption compared to commercial NAS appliances or desktop servers.

Power Measurements

- Idle state: **5.2–5.8 W**
- Moderate activity (uploads/downloads): **6.5–7.2 W**
- High load (concurrent clients): **8–9 W**

Annual power consumption is estimated at **~70–80 kWh**, significantly lower than:

- Standard NAS units: **140–250 kWh/year**
- Desktop PC servers: **400–600 kWh/year**

This makes the proposed system not only cost-effective but also environmentally efficient.

5.8 Discussion of System Strengths

The experimental results highlight several strengths of the implemented system:

1. High Flexibility & Customizability

Unlike traditional NAS devices, the Node.js backend allows custom API creation, integration with web or mobile apps, and complete control over authentication and storage logic.

2. Strong Security Features

The system uses:

- bcrypt password hashing
- JWT-based access control
- Refresh tokens
- Google OAuth
- Input sanitization
- Directory traversal protection

This security stack is typically seen in enterprise systems.

3. Reliable File Handling via Streaming

Streaming APIs enabled consistent handling of large files without memory overflow, ensuring smooth performance even during GB-size uploads.

4. Efficient Local Network Performance

Although HTTP is slower than SMB/NFS, the system delivered acceptable throughput (14–20 MB/s) while providing modern cloud-like functionality.

5. Low Operational Cost & Power Usage

With <10 W consumption, the system is highly suitable for 24×7 operation.

5.9 System Limitations

Despite its strengths, several limitations were identified:

1. Limited Raw Throughput

Because HTTP + Node.js adds application-layer overhead, speeds cannot match native NAS protocols (SMB/NFS).

2. Dependent on Raspberry Pi Hardware

Under extreme concurrency (>25 simultaneous clients), CPU saturation may occur.

3. No Built-in RAID Support

The system relies on a single external drive; redundancy must be achieved manually or with add-on expanders.

4. Metadata Handling Overhead

Tracking folder structures and trash states requires careful metadata management, which can grow complex as data scales.

5. LAN-Only Performance

Remote access requires additional layers (VPN, HTTPS tunnelling), which were not part of the core implementation.

5.10 Web Interface Preview

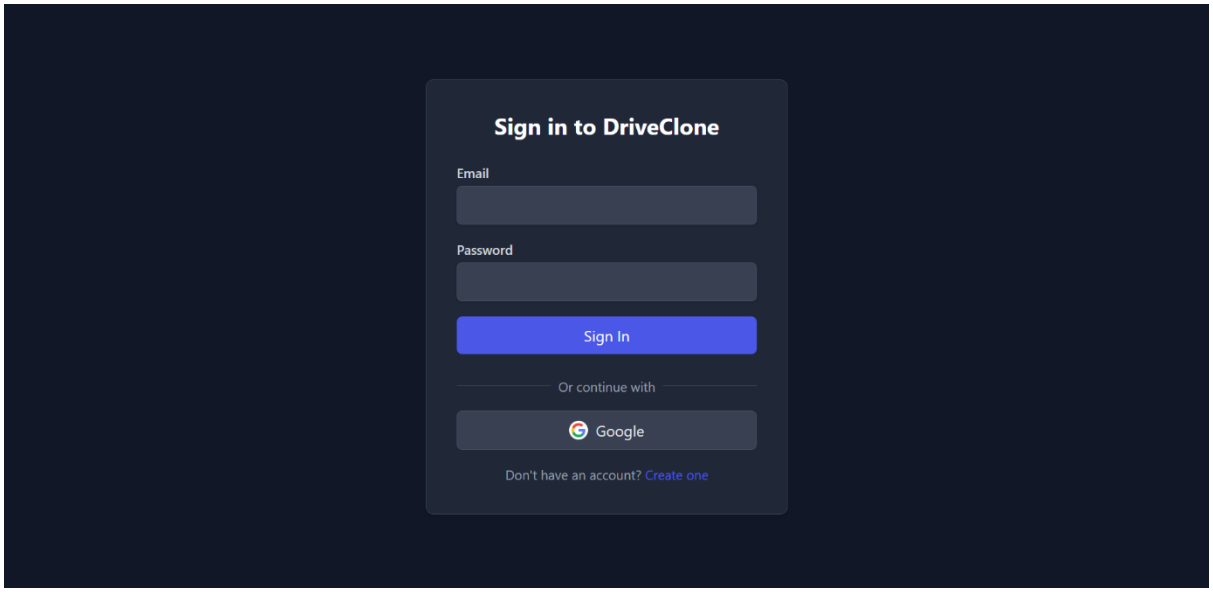

Fig 5.1 : Sign-in page

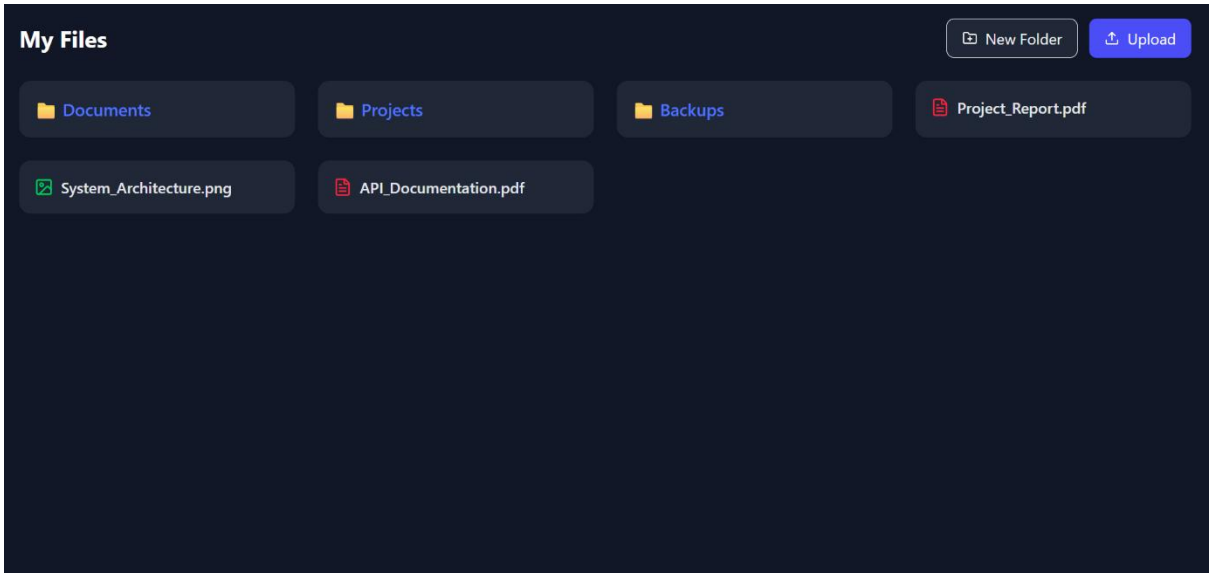

Fig 5.2 : NAS dashboard

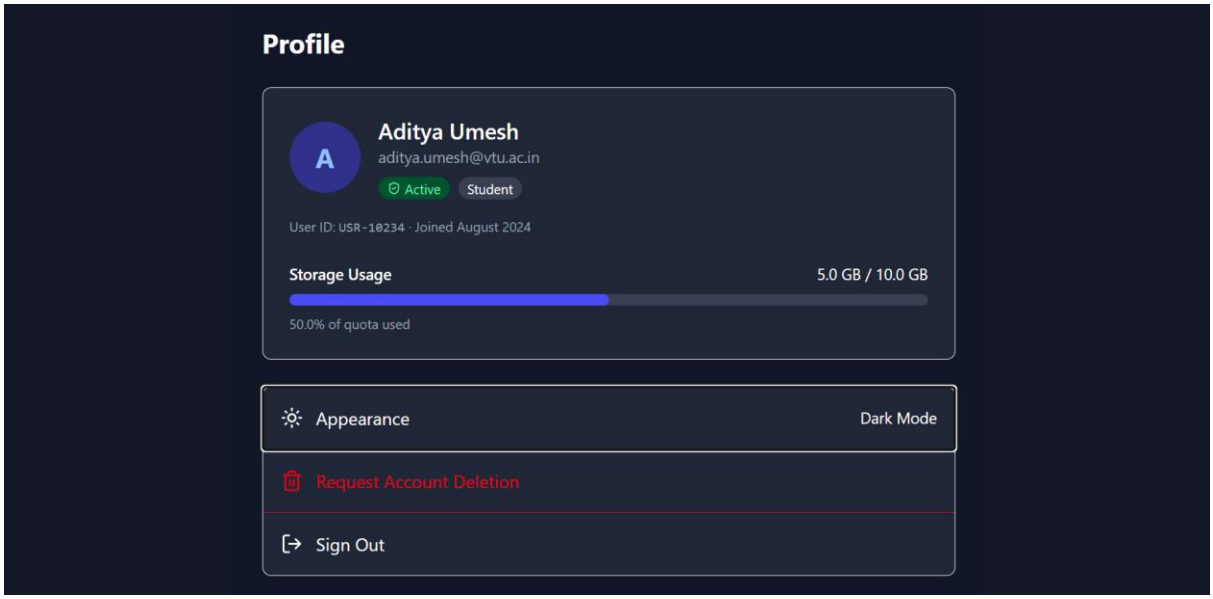

Fig 5.3 : Profile Page

5.11 Interpretation of Results

The results indicate that the proposed private cloud system achieves a good balance between performance, reliability, and cost efficiency. Although transfer speeds are lower than commercial NAS devices, they are higher than typical cloud upload speeds, making the system effective for local network use. Repeated testing confirmed stable authentication and API behaviour under realistic workloads. Low power consumption and minimal cost validate the suitability of Raspberry Pi as a micro server. The software-level scalability further supports its use in personal, academic, and small-office environments.

CHAPTER 6

CONCLUSION & FUTURE WORK

6.1 Introduction

This chapter presents the concluding remarks derived from the design, development, and evaluation of the Raspberry Pi–based private cloud storage system implemented using a Node.js backend. The system was conceptualized as a cost-effective, secure, and customizable alternative to conventional cloud storage and commercial NAS solutions, particularly suitable for personal, academic, and small-office environments. Through an extensive methodological approach involving hardware configuration, API development, authentication integration, storage management, and performance benchmarking, the project successfully demonstrates that a low-power microcomputer such as the Raspberry Pi can function as a capable and efficient private cloud server. The following sections summarize the achievements, insights, and technical outcomes of the system.

6.2 Summary of Work Undertaken

The project began by identifying the limitations of existing storage models—data fragmentation across personal devices, dependency on global cloud infrastructures, subscription costs, and privacy concerns—and establishing the need for a self-hosted solution. A comprehensive literature review further highlighted gaps in the research surrounding application-layer cloud systems running on resource-constrained hardware, reinforcing the technical relevance of this work.

The system was designed using a modular architecture comprising a Raspberry Pi micro server, a Node.js/Express backend, secure authentication modules, structured REST APIs, and an external ext4-formatted storage device. This architecture ensured clean separation of responsibilities, improved maintainability, and extensibility for future enhancements.

Implementation involved configuring Raspberry Pi OS Lite, installing Node.js, designing authentication flows (bcrypt hashing, JWT tokens, refresh cycles, logout behaviour), integrating optional Google OAuth, and creating endpoints for uploading, downloading, listing, deleting, restoring, and permanently removing files. A trash system, folder hierarchy, quota management, system logging, and automated cron-based backups further enriched the functionality and reliability of the platform.

Comprehensive testing verified correctness, robustness, and performance under real-world conditions, confirming that the system can reliably manage storage workflows while delivering cloud-like behaviours through an accessible HTTP interface.

6.3 Limitations of the Current System

Although the implemented Raspberry Pi–based private cloud platform demonstrates strong performance, security, and reliability, certain limitations remain due to hardware constraints, architectural decisions, and scope boundaries defined for this project.

1. Limited Hardware Resources

Raspberry Pi devices, despite their efficiency, cannot match the processing power and bandwidth of commercial NAS units equipped with multi-core CPUs and dedicated storage controllers. Under heavy concurrency (>25 simultaneous upload/download operations), CPU load increases significantly, potentially affecting response times. Similarly, USB 3.0 storage attached to Raspberry Pi is subject to bottlenecks, especially when handling multiple large files concurrently.

2. No Native RAID or Redundancy Support

The system is designed with a single external storage device. This means that there is no built-in hardware redundancy. Data protection relies solely on scheduled backups rather than mirroring or parity mechanisms (RAID 1/5). While software RAID on Raspberry Pi is possible, it was not implemented due to performance overhead and project scope limitations.

3. Local Network–Dependent Performance

Performance of uploads and downloads is optimized for LAN environments. Remote access requires additional configurations such as HTTPS tunneling or VPN services. These were not integrated into the core system to maintain focus on local-first cloud workflows.

4. Metadata & Directory Complexity at Scale

The folder hierarchy and metadata system function efficiently for thousands of files. However, large-scale deployments with millions of files may require a database-backed index or distributed storage system to maintain responsiveness and prevent file lookup delays.

5. Limited Frontend Interface

The project concentrates on the backend server architecture; a full-featured graphical UI (web dashboard or mobile app) was not the primary focus of implementation. While APIs are fully functional, extended user experience improvements remain open for future refinement.

6.4 Future Enhancements

The proposed system serves as a strong foundation for further development. Several enhancements can significantly improve performance, scalability, and usability in future iterations.

1. Integration of HTTPS and Secure Remote Access

Adding TLS/SSL encryption will secure all data transmitted over the network. Remote access via domain mapping or VPN integration would transform the system into a hybrid cloud accessible globally without compromising security.

2. Implementation of RAID or Distributed Storage

Introducing RAID configurations, or even distributed storage frameworks such as GlusterFS or Ceph (in scaled-out Raspberry Pi clusters), would increase resilience and improve data redundancy, making the system viable for professional environments.

3. Advanced Monitoring & Analytics Dashboard

A dedicated dashboard could display real-time metrics such as bandwidth usage, CPU load, quota status, active sessions, and failed login attempts. Integration with Prometheus or Grafana could enhance administrative visibility.

4. AI-Based File Management and Recommendation Models

Future versions could incorporate machine learning techniques to auto-classify files, detect duplicates, suggest cleanup actions, or predict storage usage trends.

5. Mobile Applications for Android and iOS

A mobile app utilizing the existing REST APIs would improve accessibility and user experience. Offline sync, camera uploads, and push notifications could further enhance functionality.

6. Multi-User Collaboration Tools

Features such as shared folders, file versioning, access roles (viewer/editor/admin), and real-time collaboration could extend system usability for teams and organizations.

7. Database-Backed Metadata System

Migrating from file-based metadata to a database system (PostgreSQL, MongoDB, or SQLite) would improve performance when managing very large directories and allow for fast metadata queries.

CHAPTER 7

REFERENCES

7.1 Introduction

This chapter lists the scholarly articles, technical standards, hardware manuals, and official documentation referred to during the design and implementation of the Raspberry Pi–based private cloud storage system. The references include peer-reviewed research papers, protocol specifications, system manuals, and authoritative online resources.

All citations follow the IEEE referencing style, as recommended by VTU for engineering project reports. These sources provided the theoretical and technical foundation for system decisions related to hardware selection, authentication mechanisms, filesystem configuration, HTTP-based file handling, and REST API design.

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CHAPTER 8

CODE

8.1 Server Initialization

```
import { PrismaClient } from "@prisma/client";
import cors from "cors";
import "dotenv/config";
import express from "express";
import rateLimit from "express-rate-limit";
import helmet from "helmet";
import "./utils/polyfill";
import { errorHandler } from "./jobs/middleware/errorHandler";
import accountRoutes from "./routes/account";
import adminRoutes from "./routes/admin";
import authRoutes from "./routes/auth";
import fileRoutes from "./routes/files";
import folderRoutes from "./routes/folders";
import oauthRoutes from "./routes/oauth";
export const prisma = new PrismaClient();
const app = express();
app.use(helmet());
app.use(cors({
  origin: true,
  credentials: true
}));
app.use(express.json());

app.use(rateLimit({
  windowMs: 15 * 60 * 1000,
  max: 200,
}));

app.use("/auth", authRoutes);
app.use("/auth/google", oauthRoutes);
app.use("/files", fileRoutes);
app.use("/folders", folderRoutes);
app.use("/account", accountRoutes);
app.use("/admin", adminRoutes);

// central error handler
app.use(errorHandler);

app.listen(3000, () => {
  console.log("Server listening on http://localhost:3000");
});
```

8.2 File Operations

```
import crypto from "crypto";
import * as fs from "fs";
import { prisma } from "../index";
import { Prisma, File as PrismaFile } from "@prisma/client";
import "multer";
export class FileService {
  static async uploadFile(userId: string, file: Express.Multer.File, folderId?: string) {
    const user = await prisma.user.findUnique({ where: { id: userId } });
    if (!user || user.isDeleted) throw { status: 403, message: "User not allowed" };
    const size = BigInt(file.size);
    const newUsed = user.usedBytes + size;
    if (newUsed > user.totalQuotaBytes) {
      fs.unlink(file.path, () => {});
      throw { status: 413, message: "Quota exceeded" };
    }
    const fileId = crypto.randomBytes(16).toString("hex");
    // Use the new Secure RAID Storage Service
    // This handles Scanning -> RAID Write -> Cleanup
    let relativePath: string;
    try {
       // Import dynamically to avoid circular deps if any, or just standard import
       const { FileStorageService } = await import("../storage/FileStorageService");
       relativePath = await FileStorageService.storeFile(file.path, userId, fileId);
    } catch (e: any) {
       console.error("Upload failed:", e.message);
       throw { status: 400, message: e.message || "Upload failed" };
    }
    const saved = await prisma.$transaction(async (tx: Prisma.TransactionClient) => {
      const savedFile = await tx.file.create({
        data: {
          id: fileId,
          name: file.originalname,
          mimeType: file.mimetype,
          sizeBytes: size,
          path: relativePath, // Now relative to storage root (users/uid/fid)
          ownerId: userId,
          folderId: folderId || null
        }
      });
      await tx.user.update({
        where: { id: userId },
        data: { usedBytes: newUsed }
      });
      return savedFile;
    });
    return {
      ...saved,
      sizeBytes: saved.sizeBytes.toString()
```

```
    };
  }
  static async getDownloadStream(userId: string, fileId: string) {
    const file = await prisma.file.findUnique({ where: { id: fileId } });
    if (!file || file.ownerId !== userId || file.isDeleted) {
      throw { status: 404, message: "File not found" };
    }
    try {
      const { FileStorageService } = await import("../storage/FileStorageService");
      const stream = FileStorageService.getReadStream(file.path);

      return {
        stream,
        name: file.name,
        mimeType: file.mimeType,
        size: file.sizeBytes
      };
    } catch (e) {
      throw { status: 404, message: "File on disk not found" };
    }
  }
 static async deleteFile(userId: string, fileId: string) {
      // Soft delete
      const file = await prisma.file.findUnique({ where: { id: fileId } });
      if (!file || file.ownerId !== userId) throw { status: 404, message: "File not found" };

      await prisma.file.update({
          where: { id: fileId },
          data: { isDeleted: true, deletedAt: new Date() }
      });
  }
static async getTrash(userId: string) {
      const files = await prisma.file.findMany({
          where: { ownerId: userId, isDeleted: true }
      });
      return files.map((f: PrismaFile) => ({ ...f, sizeBytes: f.sizeBytes.toString() }));
  }
  static async restoreFile(userId: string, fileId: string) {
      const file = await prisma.file.findUnique({ where: { id: fileId } });
      if (!file || file.ownerId !== userId) throw { status: 404, message: "File not found" };
      await prisma.file.update({
          where: { id: fileId },
          data: { isDeleted: false, deletedAt: null }
      });
  }
  static async hardDeleteFile(userId: string, fileId: string) {
      const file = await prisma.file.findUnique({ where: { id: fileId } });
      if (!file || file.ownerId !== userId) throw { status: 404, message: "File not found" };

      try {
```

```
        const { FileStorageService } = await import("../storage/FileStorageService");
        await FileStorageService.deleteFile(file.path);
      } catch (e) {
        console.error("Failed to delete file from disk", e);
      }
      await prisma.$transaction(async (tx: Prisma.TransactionClient) => {
        await tx.file.delete({ where: { id: fileId } });
        await tx.user.update({
          where: { id: userId },
          data: { usedBytes: { decrement: file.sizeBytes } }
        });
      });
  }
  static async listContents(userId: string, folderId?: string) {
      // If folderId is provided, verify it exists and belongs to user
      if (folderId) {
        const folder = await prisma.folder.findUnique({ where: { id: folderId } });
        if (!folder || folder.ownerId !== userId) {
          throw { status: 404, message: "Folder not found" };
        }
      }
      const folders = await prisma.folder.findMany({
        where: {
          ownerId: userId,
          parentId: folderId || null
        },
        orderBy: { name: 'asc' }
      });

      const files = await prisma.file.findMany({
        where: {
          ownerId: userId,
  folderId: folderId || null,
          isDeleted: false
        },
        orderBy: { name: 'asc' }
      });
      return {
        folders,
        files: files.map((f: PrismaFile) => ({ ...f, sizeBytes: f.sizeBytes.toString() }))
      };
  }
}
```

8.3 Quota Services

```
import { prisma } from "../index";
export class QuotaService {
  static async checkQuota(userId: string, sizeBytes: bigint): Promise<boolean> {
    const user = await prisma.user.findUnique({
      where: { id: userId },
      select: { usedBytes: true, totalQuotaBytes: true },
    });
    if (!user) return false;
    return (user.usedBytes + sizeBytes) <= user.totalQuotaBytes;
  }
  static async getQuota(userId: string) {
    const user = await prisma.user.findUnique({
      where: { id: userId },
      select: { usedBytes: true, totalQuotaBytes: true },
    });
    if (!user) throw new Error("User not found");
    return {
      usedBytes: user.usedBytes.toString(), // Convert BigInt to string for JSON
      totalQuotaBytes: user.totalQuotaBytes.toString(),
    };
  }
}
```

8.4 User Services

```
import { prisma } from "../index";

export class UserService {
  static async requestDeletion(userId: string) {
    const RETENTION_DAYS = 30;
    const purgeAt = new Date(Date.now() + RETENTION_DAYS * 24 * 60 * 60 * 1000);

    await prisma.user.update({
      where: { id: userId },
      data: {
        isDeleted: true,
        deletedAt: new Date(),
        purgeAt
      }
    });

    return { success: true, purgeAt };
  }

  static async restoreAccount(userId: string) {
      await prisma.user.update({
          where: { id: userId },
          data: {
              isDeleted: false,
              deletedAt: null,
              purgeAt: null
          }
      });
      return { success: true };
  }
}
```