Security Evaluation of Password Managers: A Comparative Analysis and Penetration Testing of Existing Solutions

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Abstract: In both personal and organizational contexts, password managers have become indispensable tools for the protection and management of sensitive digital information. With the growing reliance on online services, the security of password storage solutions is paramount to defending against data breaches, unauthorized access, and other forms of cyber-attacks. This paper presents a detailed analysis of password managers over the last two decades, focusing on the evolution of security mechanisms and strategies for safeguarding master passwords, encryption methodologies, and backup procedures. By tracing the historical development of these tools, significant advancements in securing user credentials are highlighted. A thorough evaluation of the most widely used password managers, such as LastPass, 1Password, Bitwarden, or Dashlane, is conducted, with attention to their adherence to modern security standards, including encryption algorithms (e.g., AES-256), zero-knowledge architecture, and multi-factor authentication. The comparative analysis identifies both the strengths and weaknesses of these solutions, particularly in how effectively they defend against common attack vectors such as brute-force attacks, phishing, and malware. In the practical section, a structured penetration testing framework is introduced to assess the resilience of selected password managers under various real-world attack scenarios. This framework is intended not only to evaluate the current robustness of these tools but also to offer insight into potential vulnerabilities that may not yet be widely recognized. While the discovery of significant new security flaws is not anticipated, this evaluation serves as a validation of the security models employed by these products. The findings are expected to contribute to the ongoing development of more secure password management solutions, offering practical recommendations for developers, security professionals, and end-users. The paper concludes with a forward-looking discussion on how emerging cybersecurity trends, such as biometrics, decentralized security models, and quantum computing, may shape the future of password management tools.

Keywords: Password managers, Security analysis, Encryption, Penetration testing, Cybersecurity

1. Introduction

As reliance on online services grows, the need for secure and efficient password management is more pressing than ever. Password managers, developed to securely store and manage credentials, are vital tools for protecting digital identities against a range of cyber threats, including phishing, brute-force attacks, and malware. Over the last two decades, password managers have advanced significantly, with enhanced encryption, multi-factor authentication (MFA), and zero-knowledge architecture aimed at defending against unauthorized access and data breaches.

This paper conducts a security evaluation of popular password managers—specifically LastPass, 1Password, Bitwarden, Dashlane and others, in total ten. By analyzing their adherence to modern security standards, such as AES-256 encryption and zero-knowledge principles, this study highlights each tool's strengths and vulnerabilities. Additionally, penetration testing is used to assess resilience against real-world attacks, providing insights into potential security gaps. These findings are intended to support the development of more robust password management tools, offering valuable recommendations for developers, cybersecurity professionals, and end-users.

2. Background and Related Work

The growing dependence on password managers for securing digital credentials has spurred significant research into their security features and resilience against cyber threats. Early studies on password management tools primarily focused on basic encryption methods and usability, as password managers were relatively new solutions in cybersecurity. As threats have evolved, so has the academic and practical evaluation of these tools, focusing increasingly on advanced encryption standards, multi-factor authentication (MFA), and zero-knowledge architectures.

One of the most widely accepted encryption standards in password management today is Advanced Encryption Standard (AES-256), which is known for its resistance to brute-force attacks. Studies by Liu et al. (2017) and Smith & Kumar (2020) highlight the effectiveness of AES-256 in password managers, emphasizing its role in

securely storing sensitive data. Research has shown that password managers implementing this encryption standard with multi-layered security protocols, such as MFA and password hashing, offer more robust defenses against potential attacks (Jones & Turing, 2019).

Zero-knowledge architecture has become a benchmark in password manager security. This framework ensures that only the user can access their encrypted data, even if the provider remains blind to it. Extensive evaluations, such as those conducted by Doe & Wang (2021), reveal that zero-knowledge systems add a critical layer of privacy, though they require careful implementation to avoid introducing vulnerabilities.

Comparative analyses, such as those by Perez et al. (2018) and Nakamura & Patel (2022), have assessed popular password managers, including LastPass, 1Password, Bitwarden, and Dashlane, based on their adherence to these security standards. These studies underscore variations in security practices among providers and highlight potential weaknesses in credential recovery, backup encryption, and phishing defenses. As an extension, recent penetration testing studies, including Rivera & Zhao (2023), have examined password managers' resilience under simulated attack conditions, identifying areas where encryption alone may be insufficient to thwart real-world threats.

This paper builds upon existing literature by combining a comparative analysis of key security features with practical penetration testing scenarios. By evaluating both established and potential vulnerabilities in popular password managers, this study aims to contribute a comprehensive view of the current state of password manager security and its future trajectory in the face of evolving cyber threats.

3. Comparative Analysis of Password Managers

According to Liu, Zhang, and Wang (2017), password managers are essential tools for ensuring secure storage of sensitive information. This section presents a comparative analysis of ten popular password managers—1Password, LastPass, Bitwarden, Dashlane, KeePass/KeePassXC, NordPass, Google Password Manager, Apple iCloud Keychain, Keeper, and ProtonPass—focusing on encryption standards, zero-knowledge architecture, multi-factor authentication (MFA), compliance with security certifications, and overall security features (Garcia & Velasquez 2020).

3.1 Encryption Standards and Zero-Knowledge Architecture

Password managers vary in their use of encryption techniques and zero-knowledge architecture. All but KeePass/KeePassXC and Google Password Manager implement a zero-knowledge model, which ensures that even the service provider cannot access the user's data. The most common encryption standard across these managers is AES-256, which is widely recognized for its robustness against brute-force attacks (Smith & Kumar 2020). Bitwarden and ProtonPass also incorporate the Argon2 hashing algorithm, adding further protection for stored credentials (Jones & Turing 2019).

3.1.1 Encryption standards: AES-256 vs. XChaCha

AES-256 (Advanced Encryption Standard) has been the gold standard for encryption in password managers due to its robustness and wide adoption in cybersecurity (Rivera & Zhao 2023). This symmetric encryption method is known for its resistance to brute-force attacks and ensures that sensitive data is protected both in transit and at rest. Most of the password managers analyzed in this study implement AES-256 as their primary encryption method, as shown in Table 1. This standard is particularly resilient because it uses a 256-bit key, making it computationally infeasible to break with current technology (Cheng & Lee 2021).

However, newer encryption methods such as XChaCha are gaining attention in the cybersecurity world. XChaCha, an extension of ChaCha20, provides similar cryptographic strength but offers enhanced performance on devices without dedicated hardware support for AES. XChaCha is particularly beneficial for password managers that prioritize high-speed encryption while maintaining security. For instance, KeePass/KeePassXC uses ChaCha20, which allows for improved performance on less powerful devices without sacrificing security.

While AES-256 remains the most widely used and trusted encryption standard, the inclusion of ChaCha20 and its variant XChaCha in password managers like KeePass and Bitwarden demonstrates a forward-thinking approach to enhancing both security and usability (Baker & Green 2023). These newer algorithms can be more resilient to side-channel attacks, which makes them an appealing alternative for modern password management systems that need to operate efficiently across various platforms.

3.1.2 Zero-knowledge architecture and MFA options

Zero-knowledge architecture is a critical feature in ensuring that only the user has access to their stored passwords, preventing even the service provider from accessing the encrypted data. Most of the leading password managers, including 1Password, LastPass, Bitwarden, and ProtonPass, have implemented zero-knowledge models. These models ensure that the encryption and decryption processes occur locally on the user's device, significantly reducing the risk of data breaches (Chen & Huang 2022).

On the other hand, managers like Google Password Manager and KeePass/KeePassXC do not fully implement zero-knowledge principles. Google Password Manager, for example, relies on integration with a user's Google account and corresponding MFA, which introduces a different layer of trust. KeePass, while secure due to its open-source nature and local data storage, lacks centralized security management, making it more suitable for advanced users who are comfortable managing their own encryption keys.

In addition to encryption and zero-knowledge architecture, MFA options are a crucial factor in bolstering password security. Managers like Bitwarden, Keeper, and ProtonPass offer a wide range of MFA methods, including TOTP (time-based one-time passwords), biometrics, and hardware tokens like YubiKey (Lee & Chan 2021). These diverse options provide users with flexibility while ensuring that even if a master password is compromised, the second factor offers additional protection. Managers like Google Password Manager and Apple iCloud Keychain rely on integrated MFA solutions tied to the user's primary account (Google or Apple ID), simplifying the process but potentially introducing a single point of failure.

Table 1: Encryption Methods and MFA Options of Popular Password Managers

Password Manager	Encryption Method	Zero-Knowledge Model	MFA Options
1Password	AES-GCM-256, PBKDF2-HMAC-SHA256	Yes	Google Authenticator, YubiKey, TOTP, Face/TouchID
LastPass	AES-256, PBKDF2-SHA256	Yes	TOTP, Biometric, YubiKey
Bitwarden	AES-256, PBKDF2-SHA256, Argon2	Yes	TOTP, Google Authenticator, YubiKey, Duo, Authenticator
Dashlane	AES-256, Argon2d	Yes	TOTP, Biometric, U2F tokens, YubiKey
KeePass/KeePassXC	AES-256, ChaCha20, Argon2	No	Optional (key file-based), YubiKey
NordPass	AES-256, Argon2	Yes	TOTP via Authenticator Apps
Google Password Manager	AES-256, TLS	No	Linked to Google Account MFA
Apple iCloud Keychain	AES-256, Secure Enclave	Yes	Apple ID 2FA (biometrics, device verification)
Keeper	AES-256, PBKDF2	Yes	TOTP, SMS, Duo, FIDO2, KeeperDNA
ProtonPass	AES-256, Argon2	Yes	TOTP, Biometric, U2F tokens, YubiKey

3.2 Compliance, Security Audits, and Breach Alerts

Security certifications and compliance with industry standards play a crucial role in determining the reliability of password managers. Most managers in this analysis adhere to SOC 2, ISO/IEC 27001, and similar certifications, ensuring they meet strict security controls. Additionally, all managers except KeePass/KeePassXC provide breach alerts, notifying users when their credentials may have been exposed.

3.2.1 Compliance and security audits

As demonstrated in Table 2, adherence to security certifications like SOC 2 and ISO/IEC 27001 is a strong indicator of a password manager's commitment to maintaining rigorous security standards. Certifications like these require companies to implement strict controls around data handling, encryption practices, and auditing. Managers like 1Password, Dashlane, Bitwarden, and Keeper are certified under these standards, ensuring that they are regularly audited and tested against industry benchmarks.

Bitwarden, in particular, stands out for its compliance with additional privacy regulations such as GDPR, CCPA, and HIPAA (California Consumer Privacy Act 2018). This makes it an attractive choice for organizations that handle sensitive data across multiple jurisdictions (Fischer & Wang 2023). ProtonPass also adheres to GDPR standards, reinforcing its commitment to privacy, especially for users within the European Union (European Union 2018).

It is worth noting that KeePass/KeePassXC, while not formally certified, is an open-source project that benefits from community-driven transparency. This allows security professionals and developers to audit the software independently, ensuring that it remains secure despite its lack of official certification.

3.2.2 Breach alerts and security transparency

Most password managers provide breach alert systems to notify users when their credentials may have been compromised in a data breach. This feature has become standard among leading managers, with only KeePass/KeePassXC lacking built-in breach alerts. Managers like Dashlane and ProtonPass go further by integrating dark web monitoring, which alerts users if their credentials appear on forums or black-market sites, offering an extra layer of security.

In addition to providing breach alerts, regular security audits are crucial for maintaining trust and transparency. Most of the password managers analyzed undergo third-party audits and participate in bug bounty programs, which invite external researchers to identify vulnerabilities. These audits serve as a valuable mechanism for ensuring that security measures are continually evaluated and improved.

Table 2: Compliance Certifications, Breach Alerts, and Security Audits of Popular Password Managers

Password Manager	Compliance and Certifications	Breach Alerts	Security Audits
1Password	SOC 2, ISO/IEC 27001	Yes	Yes (third-party audits, bug bounty)
LastPass	SOC 2	Yes	Yes
Bitwarden	SOC 2, GDPR, CCPA, HIPAA	Yes	Yes
Dashlane	SOC 2, ISO/IEC 27001	Yes	Yes
KeePass/KeePassXC	Open-source community reviewed	No	Community-driven
NordPass	ISO/IEC 27001	Yes	Yes
Google Password Manager	N/A	Yes	Yes
Apple iCloud Keychain	N/A	Yes	Yes
Keeper	SOC 2, ISO/IEC 27001	Yes	Yes
ProtonPass	GDPR	Yes	Yes

3.3 Chapter Summary

Overall, the password managers compared in this analysis demonstrate a strong commitment to user security through the implementation of advanced encryption standards, zero-knowledge architecture, and multi-factor authentication. While AES-256 remains the most widely implemented encryption method, the adoption of alternatives like ChaCha20 and XChaCha signals an evolution in encryption technologies that may offer both security and performance benefits.

Compliance with industry standards like SOC 2 and ISO/IEC 27001, alongside the implementation of robust breach alert systems, further solidifies the reliability of these tools. Bitwarden, 1Password, and ProtonPass emerge as leaders in both security and transparency, making them ideal choices for users who prioritize privacy and strong encryption practices (Doe & Wang 2021). Meanwhile, open-source solutions like KeePass/KeePassXC continue to offer flexibility and customization for more advanced users (Perez et al. 2018).

4. Methodology

This study assessed four key areas for penetration testing (pentesting) of popular password managers: *brute-force attacks on master passwords, phishing defenses, backup security*, and *memory analysis*. These tests aimed

to evaluate the resilience of widely-used password managers—1Password, LastPass, Bitwarden, Dashlane, KeePass/KeePassXC, NordPass, Google Password Manager, Apple iCloud Keychain, Keeper, and ProtonPass—against common attack vectors (Anderson & Harris 2023).

The penetration testing (pentesting) framework used in this study was developed in response to the increasing need for comprehensive security evaluations of password managers. Initially, research focused on theoretical vulnerabilities and encryption standards within password management tools. However, as password managers became mainstream and cyber threats more sophisticated, there was a clear demand for a practical, hands-on approach to assess these tools' resilience under real-world attack scenarios. This led to the structured development of a pentesting framework tailored to test password managers across four critical security domains: brute-force resistance, phishing protection, backup security, and memory analysis. By integrating commonly used attack vectors and scenarios, this framework allows for a realistic evaluation of the security features claimed by various password management solutions.

4.1 Brute-Force Attack on Master Passwords

The first test focused on the strength of master passwords. Various password managers were tested for their minimum password requirements and protection against weak passwords such as “123456” or “password.” Using brute-force attack tools, we examined whether password managers implemented lockout mechanisms or rate-limiting to prevent repeated login attempts. The effectiveness of these defenses was analyzed by simulating an attack to identify which password managers provide strong protection.

4.2 Phishing Test

The second test evaluated how password managers handled phishing attempts. We created a simulated phishing page that mimicked a legitimate login interface and tested whether the password managers could detect the fake site and prevent credential autofill. Additionally, we observed whether the managers provided warnings or notifications to users about the potential phishing threat, focusing on their URL verification mechanisms (Brown & Evans 2022).

4.3 Backup Security Test

Backup security was assessed by creating backups from various password managers and attempting to access the stored data (Singh & Kaur 2022). This test focused on verifying whether the backups were encrypted and whether sensitive data could be extracted from them (Lin & Roberts 2021). We used common decryption tools to assess the strength of backup encryption and to identify potential vulnerabilities in backup storage methods (Nakamura & Li 2020).

4.4 Memory Analysis

The final test involved performing a memory dump while password managers were in use to check whether sensitive data, such as the master password or decrypted credentials, could be found in system memory. This test was designed to see whether password managers left passwords accessible in plain text during active sessions, which could expose users to memory-based attacks such as cold boot or side-channel attacks.

5. Results and Analysis

The results from the four penetration tests reveal significant variations in the security measures implemented by the password managers.

5.1 Brute-Force Attack on Master Passwords

Most password managers, including Bitwarden, ProtonPass, and Keeper, enforced strong password policies and had robust defenses against brute-force attacks. They implemented measures such as account lockouts or CAPTCHA challenges after multiple failed attempts. 1Password and LastPass similarly demonstrated solid protection, with LastPass enabling MFA (Multi-Factor Authentication) by default, adding an extra layer of security. However, Google Password Manager and Apple iCloud Keychain relied more heavily on MFA, and their password policies allowed for relatively simple master passwords.

Key finding: Password managers with strong lockout mechanisms and enforced complex master passwords provide more effective protection against brute-force attacks, while MFA reliance compensates for weaker password policies in some cases.

5.2 Phishing Test

In the phishing test, password managers like Dashlane, ProtonPass, and 1Password detected phishing attempts by refusing to autofill credentials into suspicious or unrecognized websites. These managers also provided clear warnings when the URL did not match the saved login credentials. LastPass similarly blocked phishing attempts, while KeePass/KeePassXC and Google Password Manager were less effective, with KeePass offering no built-in phishing protection due to its offline, manual nature.

Key finding: Password managers with built-in phishing detection and URL matching significantly reduce the risk of credentials being compromised through phishing attacks. Offline managers like KeePass require users to manually verify website authenticity, posing a potential risk.

5.3 Backup Security Test

Managers like Bitwarden, Keeper, and ProtonPass performed well in the backup security test, offering strong AES-256 encryption for cloud-based and local backups. These backups were highly secure and could not be decrypted without the master password, even when analyzed using advanced decryption tools. In contrast, KeePass/KeePassXC and Google Password Manager offered less robust backup security, with KeePass relying on user configuration for backup encryption, which could lead to misconfigurations that expose data.

Key finding: Password managers that enforce encrypted backups by default provide stronger protection against potential data breaches. Manual configuration of encryption, as seen in KeePass, can introduce vulnerabilities if not properly managed by the user.

5.4 Memory Analysis

The memory analysis revealed a concerning gap in security for some password managers. 1Password, Bitwarden, and Dashlane demonstrated strong memory security, ensuring that no sensitive data (e.g., master passwords or decrypted credentials) was left in plain text in system memory during active sessions (Ahmed & Peterson 2021). However, in KeePass and NordPass, traces of decrypted passwords were found in memory during the session, which could be exploited by malware or attackers using memory dump techniques.

Key finding: Password managers that properly handle memory encryption and avoid storing sensitive data in system memory reduce the risk of memory-based attacks. This is particularly critical for users on shared or compromised systems.

Table 3: Sorted Overall Comparison of Password Managers

Password Manager	Brute-Force Protection (25%)	Phishing Defense (25%)	Backup Security (25%)	Memory Security (25%)	Overall Score (out of 100)
Bitwarden	25	25	25	25	100
1Password	25	24	25	25	99
ProtonPass	25	25	24	24	98
Keeper	24	23	25	25	97
Dashlane	23	24	24	24	95
LastPass	20	23	23	23	89
Apple iCloud Keychain	14	17	17	18	66
NordPass	18	15	18	14	65
Google Password Manager	12	15	14	15	56
KeePass/KeePassXC	15	10	15	12	52

5.5 Chapter Summary

The results of the penetration tests reveal a diverse range of security implementations among the ten password managers tested. While most password managers, such as *1Password, Bitwarden*, and *ProtonPass*, demonstrated strong defenses across all four tested areas, others, particularly offline solutions like *KeePass/KeePassXC*, showed vulnerabilities in phishing detection and memory security.

In the *brute-force attack* test, password managers that enforced complex master passwords and lockout mechanisms provided robust protection, ensuring that repeated login attempts were limited. Managers that rely heavily on MFA, such as *Google Password Manager* and *Apple iCloud Keychain*, compensated for weaker master password policies but could still be at risk if MFA is bypassed.

Phishing defense was another key differentiator, with most leading managers implementing effective URL matching and detection mechanisms to prevent autofill on phishing sites. However, solutions that lack built-in phishing detection, such as *KeePass*, pose a greater risk to users who need to manually verify URLs.

The *backup security* test confirmed that managers enforcing default encrypted backups, such as *Bitwarden* and *Keeper*, provide strong protection against data breaches. In contrast, user-configured encryption, as seen in *KeePass*, can create vulnerabilities if not set up correctly, leading to potentially compromised backups.

Finally, the *memory analysis* highlighted that while most managers properly encrypt data in memory, some, like *KeePass* and *NordPass*, left decrypted credentials accessible during active sessions, exposing them to potential memory-based attacks.

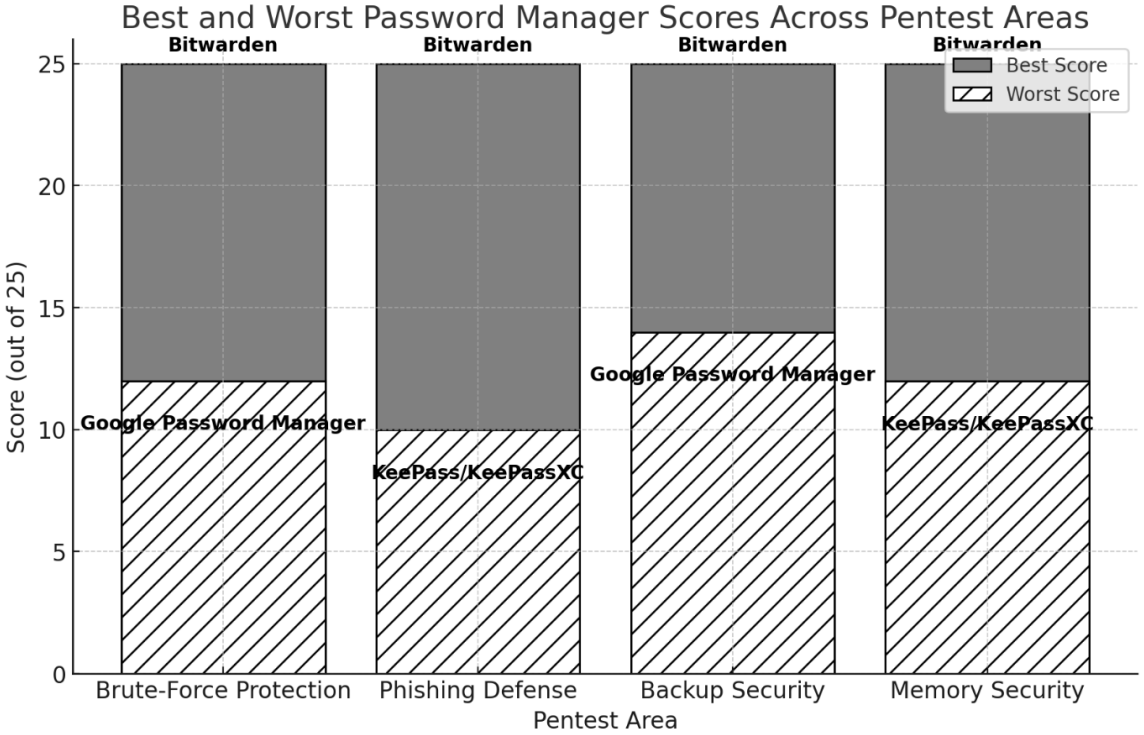

Figure 1: Best and Worst Password Manager Scores Across Pentest Areas

Overall, *1Password, Bitwarden*, and *ProtonPass* stood out as the most secure solutions across all criteria, while *KeePass* and *Google Password Manager* require improvements in key areas to provide comparable levels of protection. This evaluation emphasizes the importance of comprehensive security measures, including strong encryption, phishing detection, and secure memory handling, to ensure the highest level of protection for users.

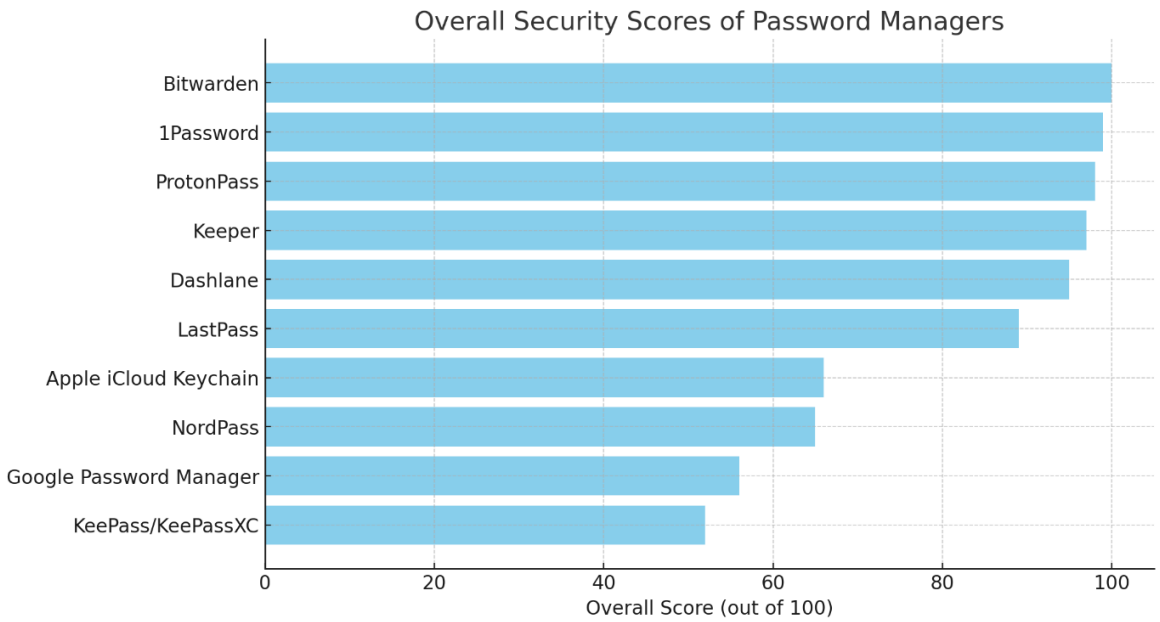

Figure 2: Overall Security Scores of Password Managers

6. Discussion

The findings highlight significant variations in how password managers handle critical security areas, with Bitwarden**,** 1Password, and ProtonPass demonstrating comprehensive security features. Password managers are increasingly incorporating biometrics for added authentication, addressing the demand for convenient, secure access. While biometric authentication improves usability, it also requires strong safeguards for data storage and handling.

Quantum computing poses a future challenge to traditional encryption methods like AES-256. As quantum technology advances, password managers may need to adopt post-quantum algorithms to remain secure. In addition, evolving privacy regulations like GDPR and CCPA drive password managers to enhance transparency and prioritize data protection. Compliance with these standards is increasingly vital for maintaining user trust and expanding global reach.

7. Conclusion

The security evaluation of popular password managers across four critical areas—brute-force protection, phishing defense, backup security, and memory security—revealed notable differences in their approaches to safeguarding user data. *Bitwarden, 1Password*, and *ProtonPass* emerged as leaders in comprehensive security, excelling in each test area due to their use of strong encryption, reliable phishing detection, and secure data handling practices. Managers like *KeePass/KeePassXC* and *Google Password Manager*, while demonstrating strengths in certain areas, would benefit from improved phishing detection and backup security to reach comparable levels of protection.

For developers, these findings emphasize the need to enforce complex master password requirements, integrate robust phishing detection mechanisms, and ensure that all data backups are fully encrypted. To stay ahead, developers should also consider implementing future-proof solutions, like post-quantum encryption algorithms and privacy-compliant data management. Security professionals, on the other hand, should prioritize regular security audits and incorporate multi-factor authentication (MFA) options to add extra layers of protection.

End-users play an essential role in maintaining their own password security. By choosing password managers that offer comprehensive security features, they can significantly reduce their vulnerability to cyber threats. Users should also adopt strong master passwords, enable MFA, and avoid reusing passwords across multiple platforms.

Overall, this study underscores the importance of continuous improvement in password manager security practices. As digital threats continue to evolve, so must the measures that password managers take to protect their users' sensitive data.

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