The approaches to quantify web application security scanners quality: a review

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Abstract
The web application security scanner is a computer program that assessed web application security with penetration testing technique. The benefit of automated web application penetration testing is huge, which web application security scanner not only reduced the time, cost, and resource required for web application penetration testing but also eliminate test engineer reliance on human knowledge. Nevertheless, web application security scanners are possessing weaknesses of low test coverage, and the scanners are generating inaccurate test results. Consequently, experimentations are frequently held to quantitatively quantify web application security scanner's quality to investigate the web application security scanner's strengths and limitations. However, there is a discovery that neither a standard methodology nor criterion is available for quantifying the web application security scanner’s quality. Hence, in this paper systematic review is conducted and analysed the methodology and criterion used for quantifying web application security scanners’ quality. In this survey, the experiment methodologies and criterions that had been used to quantify web application security scanner's quality is classified and review using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocol. The objectives are to provide practitioners with the understanding of methodologies and criterions that available for measuring web application security scanners’ test coverage, attack coverage, and vulnerability detection rate, while provides the critical hint for development of the next testing framework, model, methodology, or criterions, to measure web application security scanner quality.

Keywords
Web application security scanner, Penetration testing, Quality criteria, PRISMA.

1.Introduction
Automated web application penetration testing is becoming ubiquitous with the development of computer programs that capable of simulating tester activities of web application penetration testing. Computer programs like HTTrack [1] or Maltego [2] were invented to aid penetration tester in intelligent information gathering. The invented web application security scanners like Acunetix [3] scanned web applications for vulnerability assessment. In the meanwhile, exploitation tools like Metasploit and WFuzz are created to compromise web application confidentiality, integrity, and availability.

The web application penetration testing methodology of [4] showed web application security scanner always has a critical role in scanning the web application for vulnerability detection.

Web application security scanner simulates the actions of penetration tester of inspecting the target web application security. Subsequently, penetrating the security of web application attack vectors with selected attack strings. The web application is vulnerable if it responds positively towards the injected attack strings, or otherwise. The texts of [5] and [6] showed automated web application penetration testing is beneficial to pen-testers, which the scanner not only reduced resources, times, labour work, and costs required for conducting a web application penetration testing, the scanner also eliminates pen-tester reliance on human knowledge. Moreover, the web application security scanner preserved the human knowledge of web application penetration testing by converting them into an executable computer program.

The invention of web application security scanners has made automated web application penetration
testing a popular research trend. In this research field, practitioners have translated the web application penetration testing's testing techniques into executable programs, to enhance weak algorithms to detect new web application vulnerability, or to address the challenge of scanning modern web application that continuously expanding in both size and complexity.

A computer is merely a dummy machine that performs the calculation based on the written algorithm. Therefore, writing a sophisticated algorithm to achieve the objective of automated web application penetration testing is important in this research field. Unfortunately, humans tend to make mistakes. Moreover, the process of translating web application penetration testing's testing techniques into the executable computer program is tedious and error-prone. Hence, the designed algorithms are not always perfect, and the issue of false positives and false negatives are common for automated web application penetration testing. The false positives are consumed pen-tester extra effort and times to eliminate the fake vulnerability, while the false negatives are impaired pen-tester judgement in deciding an under-test web application security. Consequently, documents such as [6–10] are labelling web application security scanners as inaccurate and untrustworthy. This elaborate the phenomena of why experimentations are often held to quantify the web application security scanner’s quality.

An intriguing discovery is that the methodology and criteria used for measuring web application security scanner's quality are varying in existing publishing manuscripts. Moreover, there is neither a standard nor a technical document by authorized parties that defined the approach for quantifying web application security scanner's quality. Although web application security consortium (WASC) did publish web application security scanner evaluation criteria (WASSEC) [11] in the year of 2009. However, WASSEC has been just a checklist that described the features of the web application security scanner. Moreover, the corresponding checklist has never received any update for the year it was published. The NIST special publication 500-269 [12] published by the NIST SAMATE project is another out-dated technical document that contained the similar content. Therefore, in this paper, preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocol is used to classify and review the experiment methodology of published conference proceedings and journal papers that had the quality of web application security scanner quantified, to convey the compelling approach of measuring web application security scanner's quality.

The remaining part of the survey is consists of following sections. Section 2 defines the web application security scanners. Section 3 elaborates the concept of quantifying the web application security scanner’s quality. Section 4 presents the literature review's methodology. Subsequently, section 5 reviews the published methodologies. Section 6 classifies the manuscripts based on the selected indices. Finally, section 7 concluded the survey paper with the conclusion remarked.

2. Understanding of web application security scanner
Web application security scanner is a computer program that assesses web application security via simulating the pen-tester action of penetrating the web application security selected attack strings [13–16]. Figure 1 showed the general architecture of the web application security scanner.

The white box, black box, and hybrid web application security scanner are created to automatically assess web application security in either black box or white box testing environment. The black box testing environment is a testing environment that web application codes are not reachable, while white box testing environment has the total opposite meaning. Therefore, white box web application security scanners perform the vulnerability assessment by inspecting the propagation of malicious data on web application codes via a control flow graph (CFG) or data flow graph (DFG) [17–21]. On the other hand, black box web application security scanner assesses web application security by inspecting the web application execution behaviours for anomalies detection [22–26].

Hybrid web application security scanners are unique in such a way that both software static and dynamic testing techniques are used to assess the web application security scanner. The hybrid web application security scanner parsed the code and also examines the web application execution behaviours. According to [27] and [28], the software static and dynamic testing techniques are integrated to improve the test coverage and to reduce the possibility of producing the false positive and false negatives.
Web application security scanners scan a web application security with passive and active scanning. In the passive scanning, the scanner collects information of under-test web application with reconnaissance algorithm. Then, in active scanning, exploitation is performed to compromise web application confidentiality, integrity, or availability using the security penetration algorithm. This includes vulnerability detection with information flow analysis or anomaly detection. Therefore, a web application security scanner generally contains a reconnaissance component, security penetration component, and vulnerability detection component [20, 29–31].

Figure 1 The general architecture of web application security scanner

3. The web application security scanner’s quality quantification

The web application security scanner’s quality is often quantified to investigate strengths and limitations of existing algorithms, or to evaluate web application security scanner or recently designed algorithm. According to the literature of [9, 32–34], quantification of web application scanner’s quality is achievable by challenging web application security scanner’s features with test-beds. The practiced experiment methodology usually consists of preparation, execution, and reporting phases. The preparation phase defined the experiment’s objectives and scopes. The preparation phase also includes having the selected test-beds and web application security scanners configured and installed. Then, in the execution phase, web application security scanners are configured to scan the test-beds. Lastly, collected experimental results are charted and filed in the reporting phase. The virtualization is common in existing experiment methodologies for reducing both the complexity and cost required, to set up a web application penetration testing lab. The guideline to set up a virtual penetration lab is available in [35].

4. The methodology

The paper conducts the survey based on the PRISMA protocol of [36]. The completeness and transparency of PRISMA protocol have made PRISMA protocol the methodology of this survey. Figure 2 showed the flow diagram of PRISMA protocol.

PRISMA protocol has an intriguing subject systematically reviewed with these four activities, namely identification, screening, eligibility, and included.

Identification: International conference proceedings and journal papers of six major publishers, which are The Institute of Electrical and Electronic Engineers
Seng et al. (IEEE), Emerald Insight, Association for Computing Machinery (ACM), ScienceDirect, Springer, and Google Scholar, were surveyed in this survey paper. Manuscripts of this area of interest were collected from these publishers using the keywords of ‘web application penetration testing’, ‘automated web application penetration testing’, ‘web application security scanner’, ‘web application security testing’, ‘web vulnerability scanner’, and ‘web pen-test’. Overall, 290 manuscripts were retrieved with keywords stated above.

**Screening:** In this screening process, 114 manuscripts were discarded to eliminate the duplication. In the meanwhile, the remaining 144 manuscripts were carried forward for full-text reading.

**Eligibility:** In this phase, full-text of 144 manuscripts were comprehensively reviewed, to define their eligibility. The process had 54 manuscripts discarded, because of the poorly executed experiment methodology.

**Included:** Finally, experimental methodologies of elected manuscripts are qualitatively and quantitatively synthesized.

![Flow diagram of PRISMA protocol](image)

**Figure 2** Flow diagram of PRISMA protocol

**4.1 Data quantification**
The final stage of the survey quantitatively synthesizes collected data according to selected indices. The survey categorizes the data based on indices of the year of publication, publisher, web application vulnerability, test-beds, measurement metric, and web application security scanner. This data are quantified to deliver practitioners with the compelling approach of quantifying web application security scanner’s quality. In addition to that, it is to provide future works with critical hints of designing next testing framework, measurement metric, test-bed, or model to quantify web application security scanner’s quality.

**5. Approaches for scanner’s quality quantification**
The quality of web application security scanner is quantified to achieve these four objectives, which are:

a. To compare the white box and black box web application security scanners’ quality.
b. To clarify web application security scanners’ strengths and limitations.

c. To benchmark a recently proposed algorithm.

d. To clarify the web application security scanner’s test coverage.

In this section, the corresponding experimentations are reviewed to show their findings and methodologies.

5.1 White box and black box scanners comparison

The experiment distinguishes the state-of-the-art of white box and black box web application security scanner. It is also to clarify the strengths and limitations of white box and black box web application security scanners in vulnerability detection. The experiments were conducted by having both scanners scanned the same vulnerable web applications.

Subsequently, the obtained experimental results were compared, to clarify their performance. According to experimental results of [9] and [33], white box web application security scanners achieve better test coverage than black box web application security scanners because of the code visibility. Therefore, black box web application security scanner tends to generate the false negatives. However, white box web application security scanners are susceptible to false positives.

5.2 Clarifying scanners strengths and limitations

The web application security scanners are quantified to clarify their test coverage, scanning efficiency, attack coverage, and the capability to detect a class of web application vulnerability. The experiment was conducted by configured the scanners to scan selected vulnerable web applications. Summing up experimental results of [6, 7, 18, 22, 23, 26, 30, 34, 37–46], web application security scanners not only tends to generate false alarm, the coverage issue is quite concerning in automated web application penetration testing. Besides this, web application security scanners are exceptionally good in detecting reflected cross-site scripting and SQL injection. Unfortunately, hard work is still required to make web application security scanners detect the advance web application vulnerabilities. Moreover, the coverage issue is yielded, because of the challenge to scan, modern web applications that has rich media.

5.3 Benchmarking the algorithms

Experiments are also conducted to validate the recently designed algorithms. The objective is to ensure the algorithm had addressed the targeted research problem. The experiment has the algorithm scan the selected vulnerable web applications. Then, the algorithm is validated by comparing the collected experimental results with those obtained with existing algorithms. [47–49] experimental results showed the proposed code parsing and reverse engineering algorithms are efficient in scraping data entry points (DEPs) and attack vectors from under-test web applications. In the meanwhile, [50–60]’s experimental results showed leveraging of search-based testing technique, mutation testing technique, and genetic algorithm are effective in improving the attack coverage. Moreover, anomaly detection and information flow analysis by [8, 9, 27, 28, 31], and [61–79] are proven effective in detecting the web application vulnerability in either black box or white box testing environment. Besides this, the developed prototypes are validated in [5, 20, 25, 29], and [80–99].

5.4 Scanner coverage clarification

These experiments quantify web application security scanners by configured the scanners to crawl selected web applications. Experiment results of [80–82] showed the authors’ information knowledge manager (IKM) and topic model manages to increase the number of visited web pages by 28%. In the meanwhile, [100] experimental result showed test coverage is expandable by hooking JavaScript API onto dynamic analysis, to detect registered events, URLs, and web forms.

5.5 Related works

Several testing frameworks were proposed by practitioners to quantify web application security scanner’s quality. Authors of [101–103] introduced a testing framework that quantifies web application security scanner’s quality with fault injection technique. These frameworks defined a web application security scanner’s quality by measuring the capability of web application security scanner to detect the faults introduced with fault injection technique. Besides this, [104, 105], and [106] have proposed the alternative measurement metrics to rank web application security scanner’s quality. [104] introduced true duplication and false duplication to describe web application security scanner’s duplicate results, while [105] proposed the sensitive data flow coverage with an attempt to replace conventional branch coverage and statement coverage. In the meanwhile, [106] introduced the web application security scanner grading system to grade web
application security scanner's quality with the fuzzy classifier.

6. Classification of the methodologies
This section classifies methodologies of publishing manuscripts based on selected indices. The selected indices are the type of manuscript, the manuscript's year of publication, the manuscript's publisher, the testing technique of web application security scanner, the web application vulnerability, the test-beds, and measurement metrics used to describe web application security scanner's quality.

6.1 The assortment of academic manuscripts
The section classifies collected academic manuscripts to convey publishers that have a high interest in this subject of automated web application penetration testing. Then, this section classifies the manuscripts based on how this area of research is delivered to public. The data showed the relevant area of research were frequently published in six publishers of ScienceDirect, IEEE, ACM, Emerald Insight, Google Scholar, and Springer, which well-known for publishing books, ebooks, and peer-reviewed journals in science, engineering, and computer science. Amongst these publishers, IEEE, Springer, and the ACM have the highest publication rate of 47.8%, 18.9%, and 14.4% respectively. However, only a manuscript is from Emerald Insight, since the publisher is specialist more in fields like business and management, education, and marketing, with only several books series and journals covered the engineering. Unfortunately, relevant researches were frequently published as conference proceedings or symposiums, instead of journal papers with frequencies of 23.3% and 76.7% respectively. The Figure 3 and Figure 4 classify manuscripts by publisher and manuscripts' type.

6.2 The assortment of manuscript by publication year
The section classifies related academic manuscripts by their year of publication to convey the research trend of automated web application penetration testing. As depicted in Figure 5, this research topic is continuously gaining its popularity, begin from the year of 2000 to 2018. The research topic’s popularity is reaching its peak in the year 2014, which 16.7% of the manuscripts were published in that year. Nowadays, the trend of automated web application penetration testing remains attractive with an average of 5 manuscripts were published in the year 2015, 2016, and 2017.

6.3 The assortment of web application security scanners
The section classifies web application security scanners involved in the experiments with their testing technique and licensing to convey web application security scanners that available for automatically assessing web application security, while to deliver those most accessible for benchmarking purpose. Overall, the experiments had quantified 93 web application security scanners, which 87 of them are black box web application security scanners, while 8 of them are white box web application security scanners. The 87 black box web application security scanners showed 29 of them are open-source, 10 of them are closed software while remaining 48 web application security scanners are from academia. On the other hand, the manuscripts only had eight white box web application security scanners' quality quantified, which 5 of them are open-source, and 3 of them are developed in academia. Table 1 showed the tested web application security scanners.

Table 1 showed the tested web application security scanners. Figure 6 showed quantification of black box web application security scanners' quality were more often than white box web application security scanners. The reason is collected manuscripts are often describe automated web application penetration testing as a kind of black box software testing technique. In fact, manuscripts have a term called a static analyser to describe the automated white box web application testing. Consequently, the quality of black box web application security scanners called an Acunetix web vulnerability scanner, WebInspect and AppScan are often quantified with frequencies of 11.5%, 6.3%, and 9.9% respectively. In addition to that, 17.8% of manuscripts were tested web application security scanners developed in academia.
Figure 3 The division of academic manuscripts by publisher

Figure 4 The division of academic manuscripts by the type of document

Figure 5 The division of academic manuscript by publication year
Seng et al.

Figure 6 Frequencies “web application security scanner” was evaluated

Table 1 The assortment of web application security scanners by the licensing and testing approach

| Licensing       | Testing approach | Items                                      | The web application security scanner/ web spider/ parser |
|-----------------|------------------|--------------------------------------------|----------------------------------------------------------|
| Commercialized  | Black box        | S1  | Acunetix Web Vulnerability Scanner        |                                                          |
|                 |                  | S2  | HailStorm                                  |                                                          |
|                 |                  | S3  | WebInspect                                 |                                                          |
|                 |                  | S4  | Appscan                                    |                                                          |
|                 |                  | S5  | McAfee SECURE                              |                                                          |
|                 |                  | S6  | Qualysguard                                |                                                          |
|                 |                  | S7  | NeXpose                                    |                                                          |
|                 |                  | S8  | BurpSuite                                  |                                                          |
|                 |                  | S9  | N-Sparker                                  |                                                          |
|                 |                  | S10 | Retina                                     |                                                          |
|                 |                  | S11 | Teleport                                   |                                                          |
|                 |                  | S12 | Wapiti                                     |                                                          |
|                 |                  | S13 | W3af                                       |                                                          |
|                 |                  | S14 | WebCruiser                                 |                                                          |
|                 |                  | S15 | Wasapy                                     |                                                          |
|                 |                  | S16 | PowerFuzz                                  |                                                          |
|                 |                  | S17 | WebXSSDetector                             |                                                          |
|                 |                  | S18 | wget                                       |                                                          |
|                 |                  | S19 | Skipfish                                   |                                                          |
|                 |                  | S20 | Harvest                                    |                                                          |
|                 |                  | S21 | Vega                                       |                                                          |
|                 |                  | S22 | PownMe                                     |                                                          |
|                 |                  | S23 | N-Stalker                                  |                                                          |
|                 |                  | S24 | Mikito                                     |                                                          |
|                 |                  | S25 | WebScarab                                  |                                                          |
|                 |                  | S26 | WebRavor                                   |                                                          |
|                 |                  | S27 | WebSPHNIX                                  |                                                          |
|                 |                  | S28 | Larbin                                     |                                                          |
|                 |                  | S29 | Websecurity                                |                                                          |
|                 |                  | S30 | Web-Glimpse                                |                                                          |
|                 |                  | S31 | SQLfast                                    |                                                          |
|                 |                  | S32 | SQLmap                                     |                                                          |
|                 |                  | S33 | ARDILLA                                    |                                                          |
|                 |                  | S34 | Arachni                                    |                                                          |
|                 |                  | S35 | NTOSpider                                  |                                                          |
|                 |                  | S36 | ZAP                                        |                                                          |


## 6.4 The assortment of web application vulnerability

The section delivers web application vulnerabilities that detectable with automated web application penetration testing. Table 2 showed 54 web application vulnerabilities that detectable with automated web application penetration testing. Table 2 grouped relevant web application vulnerabilities, according to open web application security project (OWASP) Top 10 [107], with brief descriptions are provided to elaborate each class of web application vulnerability. Web application vulnerabilities are left unclassified if it doesn’t fit the OWASP top 10.

| OWASP Top 10 | Items | Vulnerability | Description (Deriving from OWASP) |
|--------------|-------|---------------|-----------------------------------|
| Injection attacks | V1 | SQL injection | Insertion of SQL queries to modify integrity, availability, confidentiality of database data. |
| | V2 | XPath injection | Compromising of integrity, availability, or confidentiality of data in XML. |
| | V3 | OS command injection | Execution of arbitrary commands in the host operating system through the vulnerable web application. |
| | V4 | Code injection | Execution/interpretation of injected code in the web application. |
| | V5 | Command injection | Execution of command on the host system through a vulnerable web application. Arbitrary scripts execution. |
| | V6 | Script injection | Incorporation of malicious data into XQuery pattern to alter the XQuery logic. |
| | V7 | XQuery injection | Manipulation of the file system and process of web server process. |
| File inclusion | V9 | Remote file inclusion | The remote inclusion of file that could bring harm to the target application. |
| | V10 | Local file inclusion | Inclusion local harmful files to the target web application. |
| | V11 | Arbitrary file upload | Upload of the malicious file that can bring harm to the target application. |
| | V12 | Arbitrary file inclusion | The inclusion of malicious file that can bring harm to the target application. |
| Session related vulnerability | V13 | Session fixation | The hijacking of the valid user session. |
| | V14 | Session prediction | Prediction of the session ID values. |
| | V15 | Session hijacking | Exploitation of web session control mechanism. |
| Broken authentication | V16 | Authentication bypass | Bypass web application's authentication scheme. |
| OWASP Top 10 | Items          | Vulnerability                  | Description (Deriving from OWASP)                                                                                                                                 |
|-------------|----------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
|             | V17            | Insufficient authentication   | Usage of weak passwords or poorly protected application.                                                                                                                                                                |
| Broken      | V18            | Broken access control          | Weakly enforced restrictions for authenticated users.                                                                                                                                                                  |
| authorization| V19            | Insufficient password discovery| Bypass password authentication schemes with weak password recovery mechanism.                                                                                                                                                                      |
|             | V20            | Insufficient authorization     | Authorized users have loosely configured restriction.                                                                                                                                                                     |
| Security    | V21            | SSL misconfiguration           | Misconfiguration of the server to force the usage of cryptographic options.                                                                                                                                              |
| misconfiguration| V22            | Insecure temporary file        | Creation and usage of insecure temporary files that lead to compromising of application security.                                                                                                                       |
|             | V23            | Predictable resource location  | Uncover hidden web content and functionality of target application.                                                                                                                                                   |
| Using       | V24            | misconfiguration               | Misconfigured application stack.                                                                                                                                                                                        |
| component    | V25            | Input sanitization             | Inappropriate input sanitization functions.                                                                                                                                                                              |
| Sensitive    | V26            | Path traversal                 | Accessing files and directories that stored outside the web root directory.                                                                                                                                              |
| data        | V27            | Error message disclosure       | Accidentally reveals of error codes.                                                                                                                                                                                      |
| exposure     | V28            | Username/ password disclosure  | Reveals of username or password.                                                                                                                                                                                         |
|             | V29            | Server path disclosure         | Reveals of server’s path.                                                                                                                                                                                                |
|             | V30            | Information leakage            | Reveals of the internal state of the application.                                                                                                                                                                       |
| Insecure     | V31            | Insecure object reference      | Direct access to protected objects by the user's supplied input.                                                                                                                                                        |
| deserialization| V32            | Code vulnerability             | Leveraged of insecure codes.                                                                                                                                                                                             |
|             | V33            | Code execution                 | Execution of injection code by the application.                                                                                                                                                                          |
| HTTP         | V34            | HTTP response splitting        | The inclusion of malicious characters in HTTP response header without being validated.                                                                                                                                    |
| manipulation| V35            | Parameter tampering            | Manipulation of the value of HTTP parameter.                                                                                                                                                                             |
|             | V36            | Parameter pollution            | Supplying of HTTP parameter with the similar name to alter the way application is interpreting the parameter value.                                                                                                      |
|             | V37            | HTTP request smuggling         | Tamper HTTP requests or responses with malformed HTTP requests.                                                                                                                                                        |
| Spoofing     | V38            | Content spoofing               | Defacement of the web application with text injection.                                                                                                                                                                   |
|             | V39            | SOAP spoofing                  | Defacement of HTTP header element known as SOAPAction.                                                                                                                                                                  |
|             | V40            | WS-addressing spoofing         | Adding of routing information to the SOAP header to allow asynchronous communication.                                                                                                                                    |
| Poisoning    | V41            | Cache poisoning                | Duplicate headers in a single header field.                                                                                                                                                                              |
|             | V42            | Cookie poisoning               | Filling in the cookie attribute to make browser send the cookie within the cross-site request.                                                                                                                              |
| Uncategorized| V43            | Abuse use of functionality     | Misused of application functions and features.                                                                                                                                                                             |
|             | V44            | Cross-site scripting           | Injection and sending of malicious scripts to the other end user.                                                                                                                                                       |
|             | V45            | Clickjacking                   | Transparent or opaque layer for malicious web browsing.                                                                                                                                                                  |
|             | V46            | Buffer overflow                | Submission of malicious data to corrupt web application execution stack.                                                                                                                                                 |
|             | V47            | Cross-site request forgery     | Force execution of malicious actions by the web application.                                                                                                                                                              |
|             | V48            | SOAP/ AJAX attack              | Injection of malicious data to alter XMLHttpRequest logic.                                                                                                                                                               |
|             | V49            | Denial of service              | Making resources of web application unavailable.                                                                                                                                                                          |
|             | V50            | Hidden field manipulation      | Disabling resources of a web application.                                                                                                                                                                                  |
|             | V51            | Drive-by download              | Injection of a legitimate web page with malicious code to infect legitimate web page.                                                                                                                                      |
In summary, the manuscripts had quantified web application security scanners' capability in detecting eight injection-based attacks, four file inclusion, three session related vulnerabilities, two broken authentication, three broken authorization, four security misconfiguration, one usage of component with known vulnerability, six data exposure vulnerability, two insecure deserialization, four HTTP manipulation, three spoofing, and eight uncategorized web application vulnerability. In existing manuscripts, the study of SQL injection and cross-site scripting are the most common with frequencies of 32.6% and 22.4% respectively, while 34.8% of the academic manuscripts covered both SQL injection and cross-site scripting. Unfortunately, evaluation of web application security scanners' quality for others web application vulnerabilities is rare as elaborated in Figure 7.

In the section delivers the test-beds that available for benchmarking web application security scanner’s quality and their pros and cons. Test-bed is a very vulnerable web application that contained a finite number of vulnerabilities or challenges [26, 37, 41, 103]. The test-bed is having a critical role in benchmarking web application security scanner’s quality. Existing experiment methodologies often quantify web application security scanners’ quality by configuring the scanners to scan selected test-beds. Then, web application security scanners' vulnerability detection rate or what that most relevant are measured to define their quality. Table 3 showed four test-beds are available to benchmark web application security scanner quality. Figure 8 showed 45.6% of experiment methodologies benchmark web application security scanner’s quality with open-source web application framework, while 17.3% and 16.3% of experimental methodologies evaluate web application security scanner's quality with educational vulnerable web applications and web application security scanner test sites respectively. Only 5.4% experiment methodologies use custom-made web application developed by students or teaching assistant due to their validity is questionable.

| OWASP Top 10 | Items     | Vulnerability                  | Description (Deriving from OWASP)                        |
|--------------|-----------|--------------------------------|---------------------------------------------------------|
| V52          | Format string bug | Injection of the input string for evaluating as a command by the web application. |
| V53          | Unvalidated redirect | Injection of malicious input to trigger malicious URL redirect. |
| V54          | Insufficient process validation | Failure in enforcing application business logic. |
| V55          | Logic vulnerabilities | Fault in application logic. |
Table 3 Test-beds for benchmarking web application security scanner’s quality

| Items | Category | Description | Pros | Cons | Test-beds |
|-------|----------|-------------|------|------|----------|
| W1    | Custom-made web application | Practitioners developed vulnerable web applications. | • No concern for committing the cybercrime. | • Never validated. • Manual testing is required to validate results validity. • Not well documented. | Custom web applications developed by a group of teaching assistants, researchers, or students |
| W2    | Educational vulnerable web application | Very vulnerable web applications that for educational purpose. | • Web application vulnerabilities are known. • Well documented. • No concern for committing the cybercrime. • Manual testing is not required. | • Limited web application vulnerabilities. • Limited challenges. • Only well-known web application vulnerabilities are testable. | Damn Vulnerable Web Application (DVWA), online bookstore, WebGoat, Gryyere, P0wnMe!, MultiLiLae, YAVWA, WIVET |
| W3    | Web application security scanner test sites | Test-site that specifically for benchmarking web application security scanner. | • Web applications vulnerability is known. • Well documented. • No concern for committing the cybercrime. • Manual testing is not required. | • Limited web application vulnerabilities. • Limited challenges. • Only well-known web application vulnerabilities are testable. | WackoPicko, PCI, MatchIt, W-VST, Scan-bed |
| W4    | Open-source web application framework | The open-access framework that supports web application development. | • No concern for committing the cybercrime. | • Not well documented. • Manual testing is required to validate result validity. | Drupal, phpBB, WordPress, Django, SatchMo, Vanilla, Gallery, SCARF, Reference, PHPFusion, PHPBlog, PHPNuke, PHPMyAdmin, TikiWiki, PHP Gallery, MyBB, Moodle, TestLink, SquirrelMail, Elgg, FeedSearch, RssReader, LampCMS, Joomla, PhpNN, MediaWiki, OwnCloud, Tidio, Nibbleblog, Modx-CMS, Alexa top ranking sites. |
| W5    | Real-world web application | Web application live on the World Wide Web. | • Web application security scanner's capability can genuinely reveal. | • Cybercrime may be conducted. • Not well documented. • Manual testing is required to validate result validity. | |
6.6 The assortment of measurement metrics
The section delivers measurement metrics available for quantifying web application security scanner's quality. Overall, practitioners have 13 measurement metrics to scale web application security scanner's test coverage; 7 measurement metrics to compute web application security scanner's attack coverage; 18 measurement metrics to measure web application security scanner's vulnerability detection rate; 5 measurement metrics to measure web application security scanner's scanning efficiency. The test coverage described the part of a web application that successfully scanned by a web application security scanner. In the meanwhile, attack coverage explains DEP that had been penetrated with attack payloads, while vulnerability detection rate elaborate web application vulnerability that successfully detected by a web application security scanner. On the other hand, scanning efficiency elaborates the time required to complete a vulnerability scanning session. Table 4 showed the stated measurement metrics used to quantify web application security scanner's quality.

Table 4 Measurement metrics to quantify web application security scanner quality

| Criteria             | Items       | Metrics                          | Description (By the authors)                                                                 |
|----------------------|-------------|----------------------------------|---------------------------------------------------------------------------------------------|
| Test coverage        | M1          | Number of URLs                   | The number of URLs that a web application security scanner had visited.                      |
|                      | M2          | Number of networks generated     | The number of networks produced by a web application security scanner in a vulnerability scanning session. |
|                      | M3          | Number of web pages visited      | The number of web pages visited by a web application security scanner in a vulnerability scanning session. |
|                      | M4          | Code coverage                    | The degree of web application source code that is tested by a web application security scanner. |
|                      | M5          | Test coverage                    | The degree of a web application that had been successfully tested by a web application security scanner. |
|                      | M6          | Number of links                  | The number of links that a web application security scanner had successfully retrieved.       |
|                      | M7          | Surface coverage                 | Surface and sink coverage retrieved by a web application security scanner.                    |
|                      | M8          | Testing level                    | Description of the testing approach, either in a black box or white box manner.             |
|                      | M9          | Number of data extracted         | The number of data that successfully extracted.                                             |
|                      | M10         | Capability to bypass authentication scheme | Description of the ability of a web application security scanner in provides an authentication scheme with valid data. |
|                      | M11         | Reachability scores              | The faction of retrieved entry points over the entry points of a web application.            |
|                      | M12         | Number of forms retrieved        | The number of web forms that a web application security scanner manages to retrieve.          |
| Criteria                | Items                          | Metrics                  | Description (By the authors)                                                                                                                                                                                                                                                                                                                                 |
|------------------------|-------------------------------|--------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Attack coverage        | M13                           | Number of injection point | The number of entry points that retrievable by a web application security scanner.                                                                                                                                                                                                                                                                               |
|                        | M14                           | Number of vector         | The number of inputs used to test a web application.                                                                                                                                                                                                                                                                                                           |
|                        | M15                           | Granularity of test case | Description of the object that constitutes a test case.                                                                                                                                                                                                                                                                                                        |
|                        | M16                           | Source of test case      | Description of artefacts used to generate the test case.                                                                                                                                                                                                                                                                                                       |
|                        | M17                           | Test case generation     | Description of approach that converts the source of test cases into a set of test cases.                                                                                                                                                                                                                                                                       |
|                        |                               | Test case generation     | The number of retrievable paths.                                                                                                                                                                                                                                                                                                                                |
|                        | M19                           | Number of test case      | Amount of test cases produced by a web application security scanner in a scanning session.                                                                                                                                                                                                                                                                     |
| Vulnerability detection| M20                           | Number of vulnerability  | The number of vulnerability produced by a web application security scanner.                                                                                                                                                                                                                                                                                     |
|                        | M21                           | Number of false positive | The number of unreal vulnerability produced by a web application security scanner.                                                                                                                                                                                                                                                                              |
|                        | M22                           | Number of false negative | The number of vulnerability missed by a web application security scanner.                                                                                                                                                                                                                                                                                     |
|                        | M23                           | Number of true positive  | The number of benign vulnerabilities reported by a web application security scanner.                                                                                                                                                                                                                                                                            |
|                        | M24                           | Number of true negative  | The number of benign vulnerabilities that not reported by a web application security scanner.                                                                                                                                                                                                                                                                     |
|                        | M25                           | F-measure                | Harmonic means of recall and precision.                                                                                                                                                                                                                                                                                                                        |
|                        | M26                           | Recall                   | The probability to produce a benign vulnerability.                                                                                                                                                                                                                                                                                                              |
|                        | M27                           | Precision                | The fraction of benign vulnerability from vulnerabilities reported.                                                                                                                                                                                                                                                                                              |
|                        | M28                           | Detection score          | The fraction of vulnerability detected over vulnerabilities that possessed by a test-bed.                                                                                                                                                                                                                                                                        |
|                        | M29                           | Number of true vulnerability | The number of benign vulnerabilities.                                                                                                                                                                                                                                                                                                                         |
|                        | M30                           | Number of false alarm     | The number of false positives and false negatives                                                                                                                                                                                                                                                                                                             |
|                        | M31                           | Detection rate           | The ratio of the found vulnerabilities.                                                                                                                                                                                                                                                                                                                         |
|                        | M32                           | Vulnerability coverage   | Amount of vulnerability that detectable.                                                                                                                                                                                                                                                                                                                        |
|                        | M33                           | Detection coverage       | Percentage of detectable vulnerabilities.                                                                                                                                                                                                                                                                                                                        |
|                        | M34                           | Number of true duplication | The number of duplicate true positives.                                                                                                                                                                                                                                                                                                                         |
|                        | M35                           | Number of false duplication | The number of duplicate false positives.                                                                                                                                                                                                                                                                                                                        |
| Efficiency             | M36                           | Coverage                 | The number of vulnerabilities detected.                                                                                                                                                                                                                                                                                                                          |
|                        | M37                           | Fitness                  | The number of vulnerability covered by a test case.                                                                                                                                                                                                                                                                                                              |
|                        | M38                           | Scanning time            | Amount of time required to complete a vulnerability scanning.                                                                                                                                                                                                                                                                                                  |
|                        | M39                           | Parsing time             | Amount of time required to complete parsing a set of codes.                                                                                                                                                                                                                                                                                                   |
|                        | M40                           | Automation level         | The capability to complete a scanning session without tester involvement.                                                                                                                                                                                                                                                                                        |
|                        | M41                           | Processing overhead      | Amount of extra time required to complete a scanning session.                                                                                                                                                                                                                                                                                                   |
|                        | M42                           | Productivity             | Average time required to generate a test case.                                                                                                                                                                                                                                                                                                                 |

In existing academic manuscripts, it is common that web application security scanners were quantified to measure their vulnerability detection rate. Therefore, Figure 9 showed measurement metrics like the number vulnerability, the number of false positives and the number of false negatives are the three most common measurement metrics used to measure web application security scanner’s quality with frequencies of 24.2%, 20.8%, and 5.6% respectively. However, [33] had defined F-measure as the most suitable measurement metrics to measure web application security scanner’s quality.
5. Conclusion and future work

Quantifying a web application security scanner's quality with sophisticated methodology is essential for the following reasons. Firstly, a sophisticated methodology helps in accurately defining web application security scanner's strengths and limitations, especially in locating weakly designed algorithms. Secondly, to deliver a platform to allow researchers scientifically and precisely present their concept, idea, algorithm, or achievement in the field of automated web application penetration testing to the public. Third and the last, precise methodology are significantly effecting advancement of this research field. Unfortunately, existing 90 academic manuscripts, neither have a standard methodology nor measurement metric to quantify web application security scanner's quality, although the relevant study is common. There is only a common practice that web application security scanner’s quality was quantified by configuring the scanner to scan selected test-beds. Then, practitioner quantified a scanner's quality by calculating the number of vulnerabilities detected. Consequently, the survey showed practitioners use the diverse set of methodologies, test-beds, web application security scanners, and measurement metrics to quantify web application security scanner’s quality.

Although the survey has presented the compelling approach to quantify the quality of web application security scanners' quality, as well as exhibit the test-beds, web application security scanners, and measurement metrics to measure web application security scanner’s quality. However, the survey delivers more research questions, instead of giving the answer of providing the sophisticated methodology to quantify web application security scanner's quality. For instance, the suitable amount of test-beds or web application security scanners to benchmark a web application security scanner or algorithm is unknown. In existing academic manuscripts, it showed the number of web application security scanners and test-beds used to benchmark a web application security scanner is ranging from the minimum number of zero to the maximum number of a thousand. Besides this, fittest measurement metrics to describe a web application security scanner's test coverage, attack coverage, vulnerability detection rate, and scanning efficiency are also unknown. The survey showed practitioners had quantified web application security scanner’s quality with less meaningful and redundant measurement metrics. Practitioners had measured web application security scanner's capability for vulnerability detection with measurement metrics of vulnerability detection rate and the number of vulnerabilities, which carries the same definition. In the meanwhile, measurement metrics of surface coverage and the number of links are too ambiguous to define web application security scanner’s test coverage. Since the scope of surface coverage is difficult to define, meantime the number of links cannot represent a web application's coverage because modern web applications not only consist of links but also other web elements that critical for vulnerability assessment. Therefore, there is an assuring future work for this area of this research. It is about producing a compelling methodology and metric system to quantify web application security scanner’s quality, to precisely deliver the findings of related research field to practitioners.
### Appendix

#### The assortment of methodologies by objectives

| Objective | Prototype scanners | The scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------|--------------------|--------------|-----------|----------------|---------|---------|
| WebSSARI  | Name unknown       | Burp Suite, W3af, Acunetix web vulnerability scanner | 230 random open-source web applications of SourceForge. | SQL injection, Cross-site scripting, Reflected cross-site scripting, Persistent cross-site scripting | Not clearly defined. | [80–81] |
|           |                    |              |           |                |         |         |
| Secubat   | Name unknown       | Wget, W3af, Skipfish | 100 random web applications | SQL injection, Cross-site scripting | The number of web pages, The number of forms visited, The number of vulnerabilities, Code coverage, The number of false alarms, The number of true vulnerabilities. | [85] |
|           |                    |              |           |                |         |         |
| ITS4      | Name unknown       | Grep | I-pay | SQL injection, Cross-site scripting | C++ and C code vulnerabilities, Input sanitation function | Elapsed scanning time. | [86] |
|           |                    |              |           |                |         |         |
| Saner     | Name unknown       | Grep | I-pay | SQL injection | C++ and C code vulnerabilities, Input sanitation function | The number of vulnerabilities. | [87] |
|           |                    |              |           |                |         |         |
| VS. WS    | Name unknown       | WebInspect, AppScan, Acunetix Web Vulnerability Scanner | 300 random web applications | SQL injection, Cross-site scripting, XPath injection | The number of true vulnerabilities, The number of false positives, The number of true vulnerabilities, The number of false positives. | [8] |
|           |                    |              |           |                |         |         |
| CIVS-WS   | Name unknown       | WebScarab, Webevator, Acunetix web vulnerability scanner | 15552 server defences | SQL injection | The number of visited web pages, The number of true positives, The number of false positives, The number of true positives, The number of false positives. | [49] |
|           |                    |              |           |                |         |         |
| Andromeda | Name unknown       | AJAXChat, Alterol, App. A, Blipom, BlueBlog, Contineo, Dlog, Friti, GestrCV, Gimp, JBboard, JpetStore, JgJobs, Photov, StrutsArticle, WebGoat | 15552 server defences | Cross-site scripting, SQL injection | The number of vulnerabilities, The number of false positives, The number of vulnerabilities, Elapsed scanning time. | [88] |
|           |                    |              |           |                |         |         |
| XSS analyser | Name unknown     | PHPBlog, PHPNuke, Gallery, PhpMyAdmin | 15552 server defences | Cross-site scripting | The number of vulnerabilities, The number of false positives, The number of vulnerabilities. | [50] |
| Pixy      |                    |              |           |                |         |         |
| Objective | Prototype scanners | The scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------|--------------------|--------------|-----------|----------------|---------|---------|
| Multi-agent scanner | AppScan, WebInspect | Serendipity, Yapi, Drupal | Test-beds | Stored cross-site scripting, SQL injection | The number of vulnerabilities. | [89] |
| Attack Injection Tool | TikiWiki, phpBB, MyReferences, Timeclock-software, RoomPhipalning, PHP inventory, Green Deskiny, Meshoutbox | SQL injection, Cross-site scripting | Test-beds | SQL injection | The number of vulnerabilities. | [101] |
| Name unknown | AppScan, WebInspect, Open-source blogging platform, Open-source customer management | Not clearly defined | Test-beds | SQL injection | The number of false positives. | [20] |
| RWSS | AppScan, WebInspect, Open-source blogging platform, Open-source customer management | Not clearly defined | Test-beds | SQL injection | The number of false positives. | [90] |
| Name unknown | Employee directory, Bookstore, Events, Classified, Portal | Command injection attack | Test-beds | SQL injection | The number of false positives. | [65] |
| Wasapy | Skipfish, W3af, Wapiti | PHPBB, SecurePage, Hardware Store, Insecure, Damn vulnerable web application, 6 self-developed web applications, | Test-beds | SQL injection | The number of false positives. | [66] |
| Wasapy | Skipfish, W3af, Wapiti | PHPBB, SecurePage, Hardware Store, Insecure, Damn vulnerable web application, 6 self-developed web applications, | Test-beds | SQL injection | The number of false positives. | [70] |
| WASC | PHP-Post, Jupiter CMS, PHP Gallery, Absolute path traversal, MyBBboard | PHPBB, SecurePage, Hardware Store, Insecure, Damn vulnerable web application, 6 self-developed web applications, | Test-beds | SQL injection | The number of false positives. | [69] |
| PAPAS | 50000 unique URLs from public database of Alexa | PHPBB, SecurePage, Hardware Store, Insecure, Damn vulnerable web application, 6 self-developed web applications, | Test-beds | SQL injection | The number of false positives. | [29] |
| Name unknown | WebScarab | WebGoat | Test-beds | Parameter pollution, SQL injection, Cross-site scripting, Cross-site request forgery, Predictable resource location, HTTP request smuggling, HTTP response splitting, Cache poisoning, Denial of service, Content spoofing, Hidden field manipulation, Driver-by-download, Information leakage, Session fixation, Insufficient authentication, Insufficient authorization, Brute force, SQL injection, Cross-site scripting, SQL injection | The number of vulnerabilities. | [91] |
| PIUVT | Nikto2, Wikto | MveForum | Test-beds | SQL injection, Cross-site scripting, SQL injection | The number of vulnerabilities. | [51] |
| Sania | Paros | E-learning | Test-beds | SQL injection, Cross-site scripting, SQL injection | The number of vulnerabilities. | [52] |
| Objective                          | Prototype scanners                                      | The scanners                        | Test-beds                                      | Vulnerabilities                              | Metrics                                      | Authors                          |
|-----------------------------------|--------------------------------------------------------|-------------------------------------|-----------------------------------------------|----------------------------------------------|---------------------------------------------|-----------------------------------|
| Sign-WS                           | WebInspect                                             | • Bookstore                        | • SQL injection                               | false positives.                            | The number of vulnerabilities.            | [62]                             |
|                                   | Rational AppScan                                        | • Rational AppScan                  | • Detection coverage.                         |                                              |                                              |                                  |
|                                   | Acunetix web vulnerability scanner                      | • Acunetix web vulnerability scanner | • SOAP action spoofing                        | The number of false positives.              |                                              | [92]                             |
| WS-Attacker                       | Apache Axis                                            | • Apache Axis                      | • WS-addressing spoofing                      |                                              |                                              |                                  |
|                                  | JBossWS Native                                         | • JBossWS Native                   |                                              | The number of vulnerabilities.              |                                              | [93]                             |
|                                  | JBossWS CXF                                             | • JBossWS CXF                      |                                              |                                              |                                              |                                  |
|                                  | NET web service                                        | • NET web service                  |                                              |                                              |                                              |                                  |
| Name unknown                      | Top 1000 websites from Alexa                           | • Top 1000 websites from Alexa     | • Clickjacking attack                        |                                              |                                              | [94]                             |
| Vulnerability & injection tool    | TikWiki                                                | • TikWiki                          | • SQL injection                               | The number of true positives.              |                                              | [102]                            |
|                                   | phBB                                                   | • phBB                             | • Cross-site scripting                       | The number of false positives.             |                                              |                                  |
|                                   | MyReferences                                           | • MyReferences                     | • Cookie poisoning                            |                                              |                                              |                                  |
| Name unknown                      | 3 custom web applications                              | • 3 custom web applications       | • Iframe session                             |                                              |                                              | [95]                             |
|                                   |                                                        |                                     | • Session hijacking                          |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Misconfiguration                           |                                              |                                              |                                  |
| Conflieagle                       | W3af                                                   | • W3af                             | • SQL injection                               | false positives.                            | The number of vulnerabilities.            | [95]                             |
|                                   | Skipfish                                               | • Skipfish                         | • Cross-site scripting                       |                                              |                                              |                                  |
|                                   | WebSecurity                                            | • WebSecurity                      | • Cookie poisoning                            |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Iframe session                             |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Session hijacking                          |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Misconfiguration                           |                                              |                                              |                                  |
| SOA-Scanner                       | TV-Showes                                              | • TV-Showes                        | • XPath injection                             | false positives.                            | The number of vulnerabilities.            | [71]                             |
|                                   | FeedRegistry                                           | • FeedRegistry                     |                                              |                                              |                                              |                                  |
|                                   | TV-Helper                                              | • TV-Helper                        |                                              |                                              |                                              |                                  |
|                                   | FeedSearch                                             | • FeedSearch                       |                                              |                                              |                                              |                                  |
|                                   | RssFeeder                                              | • RssFeeder                        |                                              |                                              |                                              |                                  |
| SQLIVDT                           | W3af                                                   | • W3af                             | • SQL injection                               | false positives.                            | The number of vulnerabilities.            | [72]                             |
|                                   | Nikto                                                  | • Nikto                            | • The number of false positives.             |                                              |                                              |                                  |
|                                   | Wapiti                                                 | • Wapiti                           | • Test coverage                              |                                              |                                              |                                  |
|                                   | Vega                                                   | • Vega                             | • The number of false positives.             |                                              |                                              |                                  |
|                                   | ZAP                                                    | • ZAP                              | • The number of false negatives.             |                                              |                                              |                                  |
|                                   | Acunetix web vulnerability scanner                      | • Acunetix web vulnerability scanner |                                              |                                              |                                              |                                  |
|                                   |                                                        |                                     |                                              |                                              |                                              |                                  |
| LiGRE                             | PownMe!                                                | • PownMe!                          | • Cross-site scripting                       | false positives.                            | The number of vulnerabilities.            | [53]                             |
|                                   | W3af                                                   | • W3af                             | • The number of vulnerabilities.             |                                              |                                              |                                  |
|                                   | Wapiti                                                 | • Wapiti                           | • The number of false positive.              |                                              |                                              |                                  |
|                                   |                                                        |                                     | • The number of false negative.              |                                              |                                              |                                  |
| ETSSDetector                      | Acunetix web vulnerability scanner                      | • Acunetix web vulnerability scanner | • Cross-site scripting                       | false positives.                            | The number of vulnerabilities.            | [54]                             |
|                                   | N-Stalker                                              | • N-Stalker                        | • The number of vulnerabilities.             |                                              |                                              |                                  |
|                                   | WebCrusher                                             | • WebCrusher                       | • The number of false positives.             |                                              |                                              |                                  |
|                                   | PowerFuzz                                              | • PowerFuzz                        | • The number of false negatives.             |                                              |                                              |                                  |
|                                   | WebSecurity                                            | • WebSecurity                      | • Elapsed scanning time.                     |                                              |                                              |                                  |
|                                   | WebXSSDetector                                         | • WebXSSDetector                   | • The number of web pages.                   |                                              |                                              |                                  |
| Name unknown                      | W3af                                                   | • W3af                             | • Elapsed scanning time.                     |                                              |                                              | [47]                             |
|                                   | Wapiti                                                 | • Wapiti                           | • The number of web pages.                   |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Elapsed scanning time.                     |                                              |                                              |                                  |
|                                   |                                                        |                                     | • The number of vulnerabilities.             |                                              |                                              | [47]                             |
|                                   |                                                        |                                     | • Elapsed scanning time.                     |                                              |                                              |                                  |
| NVS                               | Acunetix Web Vulnerability Scanner                     | • Acunetix Web Vulnerability Scanner | • SQL injection                               | false positives.                            | The number of vulnerabilities.            | [73]                             |
|                                   | NetSparkler                                            | • NetSparkler                      | • The number of false positives.             |                                              |                                              |                                  |
|                                   | Web Cruiser                                            | • Web Cruiser                      | • The number of false negatives.             |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Elapsed scanning time.                     |                                              |                                              |                                  |
|                                   |                                                        |                                     | • The number of web pages.                   |                                              |                                              |                                  |
|                                   |                                                        |                                     | • Elapsed scanning time.                     |                                              |                                              | [47]                             |
|                                   |                                                        |                                     | • The number of vulnerabilities.             |                                              |                                              | [47]                             |
|                                   |                                                        |                                     | • Elapsed scanning time.                     |                                              |                                              | [47]                             |

302
| Objective | Prototype scanners | The scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------|-------------------|--------------|-----------|----------------|---------|---------|
| Name unknown | Acunetix web vulnerability scanner | WebInspect | Jobsite | SQL injection | The number of false positives, Test coverage. | [63] |
| Name unknown | WebInspect | AppScan | Education | XPath injection | True positives, Test coverage. | [31] |
| WebGuardia | Not clearly defined | WackoPicko | HR | SQL injection | The number of vulnerabilities. | [96] |
| WAP | Pissy | phpMyAdmin | Multllidae | SQL injection | The number of vulnerabilities. | [27] |
| Name unknown | WebInspect | AppScan | ProductDetail | Cross-site scripting | Detection coverage. | [64] |
| Name unknown | Wasapy | Skipfish | phpBB-3 | Unvalidated redirect | The number of false positives. | [68] |
| Name unknown | W3af | Wapiti | SecurePage | Secure direct object references | The number of false negatives. | |
| Name unknown | WebInspect | AppScan | HardwareStore | Security misconfiguration | The number of false negatives. | |
| Name unknown | Acunetix Web Vulnerability Scanner | WebInspect | Insecure | SQL injection | The number of false negatives. | |
| Name unknown | Acunetix Web Vulnerability Scanner | WebInspect | W3af | SQL injection | The number of false negatives. | |
| Name unknown | FindBugs | ChangePaymentMethod | SQL injection | The number of false positives. | [97] |
| Name unknown | ChangePaymentMethod | NewCustomer | SQL injection | The number of false positives. | [105] |
| SQLFast | WebGoat | Damn vulnerable web application (DVWA) | Damn vulnerable web application (DVWA) | SQL injection | The number of false positives. | [79] |
| Idea | SQLFast | WAVSEP | Yet another vulnerable web application (YAVWA) | SQL injection | The number of false positives. | [55] |
| Name unknown | Teleport | WebInspect | SourceForge | SQL injection | The number of false positives. | [84] |
| Name unknown | WebInspect | AppScan | 230 random web applications | Cross-site scripting | The number of false positives. | [55] |
| PMVT | Rational AppScan | NTOSniper | Stud-e | SQL injection | The number of false positives. | [74] |
| ANOVA | Web applications from cyber security bulletin | APhpKb | Cross-site scripting | SQL injection | The number of false positives. | [74] |
| PMVT | Skippfish | Arachni | Multi-step cross-site scripting | SQL injection | The number of false positives. | [74] |
| Objective       | Prototype scanners | The scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------------|--------------------|--------------|-----------|----------------|---------|---------|
| jAk             | Skipfish           | WebInspect   | SQL injection | Cross-site scripting | The number of tests. | [100] |
| THAPS           | Acunetix web vulnerability scanner | MyReferences | SQL injection | Cross-site scripting | The number of vulnerabilities. | [48] |
| Name unknown    | Acunetix web vulnerability scanner | WatchFine AppScan | SQL injection | Cross-site scripting | The number of vulnerabilities. | [103] |
| XqueryFuzzer    | ZAP Attack Scan | Bookstore | SQL injection | Cross-site scripting | The number of vulnerabilities. | [57] |
| Name unknown    | Acunetix web vulnerability scanner | Not clearly defined | SQL injection | Buffer overflow | The number of false positives. | [75] |
| Name unknown    | Nikto              | phpBB       | Not clearly defined | Buffer overflow | The number of false positives. | [76] |
| WAPTT           | W3af               | 3 vulnerable web application from postgraduate students and teaching assistants. | SQL injection | Cross-site scripting | The number of vulnerabilities. | [28] |
| BIOFUZZ         | ARDILLA            | WebChess    | SQL injection | The number of vulnerabilities. | [58] |
| KamaleonFuzz    | P0wnMe            | P0wnMe!     | Cross-site scripting | The number of false positives. | [59] |
| Cross-request scanner (CRS) | HSBC | BEA | Parameter tampering | The number of true positives. | [25] |
| XSS Peekr       | Acunetix web vulnerability scanner | WackoPicko. | Cross-site scripting | The number of vulnerabilities. | [23] |
| Inferential     | Acunetix web vulnerability scanner | WAVSEP    | SQL injection | The number of false positives. | [77] |
| Objective | Prototype scanners | The scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------|-------------------|--------------|-----------|-----------------|---------|---------|
| XiParam   |                   |              | 5 web applications from GotoCode Custom developed web applications | XQuery injection Parameter tampering | URLs. False positive rate. The number of vulnerabilities. The number of attack requests. The number of successful attacks. The number of vulnerable forms. The number of false positives. The number of false negatives. | [60] |
| Not clearly defined | 1854 PHP projects on Github | SQL injection Command injection Code injection Arbitrary file read/write Cross-site scripting Session fixation Logic flaws | The number of URLs. The number of Forms. The number of vulnerabilities. The number of false positives. The number of false negatives. Elapsed scanning time. The number of generated network. The number of vulnerabilities. The number of false positives. | |
| DetLogic | LogicScope WackoPicko Scarf OpenIT Puzzlemall | Acunetix web vulnerability scanner HailStorm WebInspect Rational AppScan McAfee SECURE QualysGuard.PCI NeXPose | Drupal phpBB WordPress | SQL injection Cross-site scripting Arbitrary file upload Remote file inclusion OS command injection Code injection Session fixation Session prediction Authentication bypass Cross-site request forgery SSL misconfiguration Insecure HTTP methodologies Insecure temporary file Path traversal Source code disclosure Error message disclosure SQL injection Cross-site scripting Code injection Broken access control | The number of vulnerabilities. The number of false positives. | [108] |
| Not clearly defined | WackoPicko | Acunetix web vulnerability scanner AppScan WebInspect Qualys AppScan Acunetix web vulnerability scanner WebInspect | 27 custom developed web applications 300 random web applications | SQL injection Cross-site scripting Information leakage Cross-site request forgery SQL injection XPath injection Code execution Buffer overflow Username/password disclosure | Elapsed scanning time. Detection score. Reachability score. The number of vulnerabilities. The number of false positives. | [38] |
|               |                   |              |           |                 |         | [7]     |
| Objective | Prototype scanners | The scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------|-------------------|--------------|-----------|----------------|---------|---------|
| Seng et al. | | | | | | |
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| Objective | Prototype scanners | Test-beds | Vulnerabilities | Metrics | Authors |
|-----------|--------------------|-----------|----------------|---------|---------|
|           | BurpSuite          | WebGoat   | Cross-site scripting | Coverage | [43]    |
|           | ZAP Proxy          | Multilidae II |               |         |         |
|           |                    | Dumm vulnerable web application (DVWA) |               |         |         |
|           |                    | Bodgit     |               |         |         |
|           |                    | Gruyere    |               |         |         |
|           |                    | WAVSEP     | SQL injection  |         | [44]    |
|           |                    | AltonoMutual | Cross-site scripting |         |         |
|           |                    | Web scanner test site |               |         |         |
|           |                    | WIVET      | Remote file inclusion |         |         |
|           |                    | Acunetix test sites | Path traversal / local file inclusion |         |         |
|           | Arachni            | WAVSEP     | SQL injection  |         | [45]    |
|           | Wapiti             | Multilidae II | Cross-site scripting |         |         |
|           | Skipfish           | Wapiti     | Remote file inclusion |         |         |
|           |                    | Vega       | Path traversal / local file inclusion |         |         |
|           |                    | ironWASP   |               |         |         |
|           |                    | W3af       | Null byte      | Detection rate. | [22]    |
|           |                    | Vega       | SQL injection  |         |         |
|           |                    | Arachni    | Insufficient password recovery |         |         |
|           |                    | ZAP Proxy  | Code injection  |         |         |
|           |                    | W3af       | Abuse of functionality |         |         |
|           |                    | Arachni    | XPath injection |         |         |
|           |                    | ZAP Proxy  | Insufficient process validation |         |         |
|           |                    | WebInspect | TPC-APP service | SQL injection | [33]    |
|           |                    | AppScan    | TPC-C web service |         |         |
|           |                    | Acunetix web vulnerability scanner | TPC-W web service |         |         |
|           |                    | FindBugs   |               |         |         |
|           |                    | Yasca      |               |         |         |
|           |                    | IntellijIDEA |               |         |         |
|           |                    | Teleprt    |               |         |         |
|           |                    | Web Sphnix |               |         |         |
|           |                    | Harvest    |               |         |         |
|           |                    | Larbin     |               |         |         |
|           |                    | Web-Glimpse|               |         |         |
|           |                    | Google     |               |         |         |
|           | WAVES              | NAI        | SQL injection  |         | [82, 83]|
|           |                    | Lucent     | Cross-site scripting |         |         |
|           |                    | Trend Macro |               |         |         |
|           |                    | Palm       |               |         |         |
|           |                    | Olympic     |               |         |         |
|           |                    | Apache     |               |         |         |
|           |                    | Verisign   |               |         |         |
|           |                    | Ulead      |               |         |         |
|           |                    | Cert       |               |         |         |
|           |                    | Maxtor     |               |         |         |
|           |                    | Mazda      |               |         |         |
|           |                    | Linux Journal |               |         |         |
|           |                    | Cadillac   |               |         |         |
|           |                    | Web500     |               |         |         |
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Conflicts of interest
The authors have no conflicts of interest to declare.

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