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Statistical analysis of pesticide removal by natural and waste-based adsorbents: a novel method for quantitative and green suitability assessment (GSI)

Doğal ve atık bazlı adsorbanlar tarafından pestisit gideriminin istatistiksel analizi: nicel ve yeşil uygunluk değerlendirmesi için yeni bir yöntem (GSI)

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Abstract

The accumulation of pesticide residues in aquatic environments poses significant environmental risks to ecosystem integrity and human health. This study systematically reviewed 77 peer-reviewed studies (2008–2025) on natural and waste-based adsorbents used for pesticide removal from water and conducted a comprehensive evaluation based on green chemistry principles. Adsorbent types, target pesticide groups, and removal methods were classified and statistically analyzed. A novel Green Suitability Index (GSI) was developed to quantitatively assess the environmental compatibility of adsorbents. The index is based on four main criteria: raw material renewability, process chemical minimalism, post-use waste and environmental risk, and energy–carbon reduction, producing a composite score on a 0–12 scale, where higher scores indicate stronger alignment with green chemistry principles. The findings revealed that agricultural waste-based adsorbents were the most studied group and achieved the highest environmental suitability (mean GSI = 11/12, SD = 2.75; ≈92%), followed by plant-derived natural adsorbents (mean GSI=9/12, SD = 2.25; ≈75%). In contrast, nano/modified adsorbents showed the lowest green compatibility (mean GSI = 4/12, SD = 1.00; ≈33%) due to higher synthesis energy demands and reagent use. Organophosphate pesticides were the most frequently targeted contaminants. Overall, the results demonstrate that natural and waste-based adsorbents combine high removal efficiency with superior green chemistry compliance, offering sustainable and low-impact alternatives for pesticide pollution control and eco-friendly water treatment applications.

Keywords: Pesticide adsorption, natural and waste-based adsorbents, green chemistry, quantitative evidence synthesis, statistical analysis.

Öz

Su ortamlarında pestisit kalıntılarının birikimi, ekosistem bütünlüğü ve insan sağlığı açısından önemli çevresel riskler oluşturmaktadır. Bu çalışma, 2008–2025 yılları arasında yayımlanmış 77 akademik çalışmayı sistematik olarak incelemiş ve pestisit gideriminde kullanılan doğal ve atık bazlı adsorbanları yeşil kimya ilkeleri doğrultusunda kapsamlı biçimde değerlendirmiştir. Adsorban türleri, hedef pestisit grupları ve giderim yöntemleri sınıflandırılarak istatistiksel olarak analiz edilmiştir. Bu amaçla geliştirilen Yeşil Uygunluk İndeksi (GSI), adsorbanların çevresel uyumluluğunu nicel olarak değerlendiren özgün bir yöntemdir. İndeks; hammadde yenilenebilirliği, proses kimyasal sadeliği, kullanım sonrası atık ve çevresel risk, enerji–karbon azaltımı olmak üzere dört ana kriterden oluşmakta ve 0–12 ölçeğinde puan üretmektedir. Sonuçlar, tarımsal atık bazlı adsorbanların en yaygın kullanılan grup olduğunu ve en yüksek çevresel uygunluk skoruna (ortalama GSI = 11/12, SD = 2,75; ≈%92) ulaştığını göstermiştir. Bitkisel kökenli adsorbanlar 9/12 (SD = 2,25; ≈%75), nano/modifiye adsorbanlar ise 4/12 (SD = 1,00; ≈%33) değerleriyle daha düşük uyumluluk göstermiştir. Genel olarak bulgular, doğal ve atık bazlı adsorbanların yüksek giderim verimi ile güçlü yeşil kimya uyumluluğunu birleştirerek sürdürülebilir ve çevre dostu su arıtım teknolojileri için önemli bir potansiyel sunduğunu ortaya koymaktadır.

Anahtar kelimeler: Pestisit adsorpsiyonu, doğal ve atık bazlı adsorbanlar, yeşil kimya, nicel kanıt sentezi, istatistiksel analiz.

1 Introduction

Pesticides, widely used to increase agricultural productivity, negatively impact not only the targeted pests but also environmental components. Pesticide residues, particularly those accumulating in aquatic environments, pose serious risks to public health and ecosystems due to their toxicity, persistence, and bioaccumulation [1],[2]. Traditional treatment methods developed to remove pesticides from water (e.g., chemical oxidation, coagulation, or advanced membrane technologies) are often costly, energy intensive, and environmentally unsustainable [3]. For this reason, studies on environmentally friendly and economical solutions compatible with green chemistry principles have increased, and low-cost natural adsorbents obtained from agricultural and organic waste have gained importance [4], [5]. Adsorption has become one of the most preferred methods for pesticide removal due to its advantages such as ease of operation and high removal efficiency [6], [7]. The success of this method depends on the surface properties, pore structure, and functional groups of the adsorbent used [8], [9]. Recent research has demonstrated that a wide variety of natural and waste-derived materials can serve as highly effective adsorbents. These include agricultural by-products such as corn cob [10], typha plants [11], [12], cactus leaves [13], wood sawdust and cork wastes [14], used tea leaves [15], orange peel and apricot pit [16], cork granules [17], and granular tire rubber [18]. In addition, mineral- and waste-based materials

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like black mica (Biotit) [19], waste-derived nanoparticles [20], switchgrass [21], Moringa oleifera [22] have shown promising results. Other examples include combinations of corn cob and rice husk [23], rice and wheat straw ash [24], coconut shell [25], fly ash[26], plant-derived materials [27], bamboo and coconut shell [28], watermelon rind [29], vermicompost [30], agricultural waste [31], lignocellulosic waste [32], various agricultural waste [33]. Advanced adsorbents have also been developed from ZnO-loaded activated carbon [34], organic matter (compost, humus, etc.) [35], calcined bone [36], rice husk ash [37], and other materials like cassava peel, crambe pulp, pine bark [38] and cow dung [39]. These natural resources are easily available locally and have been used in pesticide removal by increasing their surface activity with appropriate modifications [40], [41]. The effectiveness of these natural adsorbents in removing organophosphates, carbamates, and phenoxyacetic acid-derived herbicides from water has been demonstrated in many studies [8], [9]. Column studies using plant-based materials such as Moringa oleifera seeds have shown that pollutants such as atrazine can be removed with high efficiency [7]. Furthermore, hybrid biosorbent systems in the form of hydrogels have been reported to be highly effective for water-soluble pesticides [42].

This study presents a statistical synthesis of the existing literature to evaluate the performance of biosorbents in pesticide removal. While numerous individual experiments have been conducted on this topic, comprehensive quantitative meta-analysis has yet to be developed. The primary aim of this research is to synthesize data from multiple individual studies in order to generate reliable evidence regarding the alignment of pesticide adsorption processes with green chemistry principles, particularly through the use of natural and low-cost adsorbents. By generating and interpreting frequency distributions, cross-tabulations, and visual analytics, the study identifies significant patterns between adsorbent types and pesticide classes, with a focus on environmentally friendly and cost-effective materials. A key contribution of this research is the integration of the newly developed Green Suitability Index for Green Chemistry (GSI), a novel analytical framework designed to quantitatively assess the compatibility of biosorbent-based removal processes with the core principles of green chemistry. This integrative approach not only maps current research trends quantitatively but also offers a robust evaluation of the sustainability and environmental relevance of biosorbent applications in pesticide remediation.

2 Health and environmental risks of pesticides and the potential of adsorption as a green method

2.1 Environmental and health effects of pesticides

Pesticides are widely used chemicals in modern agricultural practices, but they not only increase agricultural productivity but also cause serious environmental and health problems. Numerous studies in recent years have revealed that the long-term effects of these chemicals are far more widespread than previously thought. Pesticide residues have been identified as leaching into soil, air, and surface water, threatening various ecosystem components, from aquatic organisms to bees. They are also linked to numerous human health conditions, from cancer to neurological disorders [43]–[45].

From an environmental perspective, the accumulation of pesticides in aquatic ecosystems and their bioaccumulation in living organisms is a serious problem. For example, Hladik et al. reported that pesticides used during corn seed processing were detected in dissolved and particulate forms in river systems, posing a risk of acute and chronic toxicity, particularly for fish and other aquatic organisms [45]. Similarly, Burch et al. detailed the negative impacts of pesticides on aquaculture, demonstrating that these pollutants cause behavioral changes, reproductive problems, and increased biochemical stress in fish [43]. Furthermore, another recent study examining bee populations revealed how pesticides weaken pollinator ecosystem services, posing indirect threats to biodiversity and food security [44].

The effects on human health are at least as concerning as environmental ones. Individuals exposed to pesticides through occupational or environmental means experience a wide range of health effects, from hormonal disorders and fertility problems to developmental anomalies and neurological disorders. For example, pesticide exposure has been shown to increase the risk of birth anomalies and infertility in women working in agricultural fields [46]. Another, more localized study highlights the impact of the endocrine-disrupting effects of pesticides on women's health, particularly in tropical regions like Latin America [47]. The effects of pesticides on children's health are also noteworthy. A study published by Rodrigues et al. reported that pesticide exposure in children causes developmental disorders and negative effects on the immune system [48]. In this regard, a study of greenhouse workers found high levels of pesticide residue in their serum, suggesting that this could lead to long-term genotoxic effects [49]. A significant association between pesticide exposure and childhood cancers has been suggested, indicating that children living in rural areas are particularly vulnerable to disease [50]. A study conducted with children with a history of cancer indicated that re-exposure to pesticides may facilitate disease recurrence [51]. There are also significant implications for pregnancy and child health. Pesticide metabolite levels detected in maternal urine have been found to be associated with newborn birth weight and thyroid hormone levels, with studies reporting that this effect is particularly exacerbated in the presence of iodine deficiency.

Some recent studies have shown that pesticides can impact not only physical health but also the nervous system and sensory organs. For example, the potential effects of pesticides on the auditory nervous system have been evaluated, and it has been shown that long-term exposure, in particular, is associated with sensory impairments [52]. Inflammatory biomarkers have been significantly increased in individuals exposed to pesticides, which may play a role in the development of various diseases associated with chronic inflammation [53]. Indirect exposure through food consumption also poses a health risk. It is emphasized that pesticide residues in plant-based diets should not be ignored, and that pesticide residue levels, particularly in non-organic agricultural products, should be evaluated considering their impact on human health Some authors argue that most studies in this area are conducted under laboratory conditions and therefore do not adequately represent real-life exposures, and that environmental realities should be taken into greater consideration in experimental research [54]. Some findings examining the environmental behavior of pesticides and the factors affecting exposure are also important in the context of their impact on human health. For example, the effects of microplastics on the toxicity and bioavailability of pesticides have been evaluated, highlighting the possibility that these pollutants may cause more complex health problems through synergistic effects [55].

Overall, the effects of pesticides on the environment and human health constitute a complex and intertwined problem. These effects are not limited to acute toxicological reactions; they can also lead to long-term consequences such as cancer, reproductive health disorders, nervous system disorders, and ecosystem collapse. Therefore, stricter control of pesticide use, implementation of policies that protect environmental and human health, and promotion of alternative, environmentally friendly agricultural methods are crucial.

2.2 Basic mechanism and advantages of pesticide adsorption

Adsorption is a prominent method for removing pesticides from aquatic environments due to its effectiveness and environmental friendliness. Adsorption occurs when pesticide molecules in solution adhere to a solid surface. This process generally proceeds through physical (van der Waals forces) or chemical (covalent bonds, ion exchange) interactions. The surface area, pore structure, and functional groups of the adsorbent are among the primary factors that directly affect adsorption efficiency [56], [57]. The use of natural and agricultural waste-based adsorbents has gained prominence in the context of the effective way green chemistry principles offer to reduce the use of harmful chemicals and make processes environmentally friendly [58], [59]. Local biomass sources have been frequently evaluated in research due to their low cost and environmental friendliness [16], [23], [25], [29]. Adsorbents obtained from natural sources or agricultural wastes are in strong compliance with the principles of green chemistry due to their low cost and environmental sustainability [58], [59]. Biomass materials such as orange, pomegranate, apricot, olive, rice, and corn shells facilitate adhesion by interacting with pesticide molecules thanks to the hydroxyl, carboxyl, and amine groups they contain in their structures [60]. These natural adsorbents are made more effective against pesticides by modifying their surface area, porosity, and functional groups [32], [61]. Surface modifications can increase their adsorption capacity by functionalizing them, thus making them selective against different pesticide types [62]. Studies on the removal of pesticides through adsorption have shown that the effectiveness of natural adsorbents depends on the type of pesticide, pH, temperature, and contact time [17], [63]. For example, organophosphate pesticides such as ethion, TEPP, and dimethoate have been effectively removed using modified plant waste or biosorbents [16], [64], [65].

The main advantages of the adsorption process include low energy requirements, minimized use of chemical reagents, easy applicability, and the availability of reusable adsorbent options. These processes, particularly those developed within the framework of green chemistry, offer significant contributions to both controlling pesticide pollution and improving the sustainability of waste management [58]–[60].

2.3 Green chemistry principles

Green chemistry, an approach centered on environmental protection and sustainability, aims to minimize harmful effects in chemical processes. Studies in this field demonstrate that chemistry can offer solutions that are both environmentally compatible and economically viable. Research in this field, particularly in recent years, has demonstrated that green chemistry is not limited to the laboratory but can also be successfully integrated into industrial applications [58]. The 12 principles underlying green chemistry include producing less waste, avoiding toxic chemicals, and focusing on energy efficiency and renewable resources. These principles are currently used quite effectively in some production processes. For example, studies have been conducted that emphasize the need to integrate these principles into every stage of production to achieve a sustainable polymer production cycle [59]. Studies have also demonstrated that special polymers (MIPs) used in the separation of harmful gases such as carbon dioxide can be produced using environmentally friendly methods, and that these technologies can achieve higher efficiency with lower energy consumption [56].

Another factor that has led to significant developments in this field is the adaptation of green chemistry to analytical chemistry. Studies have proposed the concept of White Analytical Chemistry, and discussions have been conducted on how to develop less environmentally damaging analytical methods. This approach considers numerous criteria, from solvents used to waste management [57]. Practical tools have been developed to evaluate efforts in this field, allowing for numerical measurement of the environmental friendliness of an analytical method [60]. This allows for easier understanding of which method is more sustainable. The applicability of green chemistry is particularly important for developing countries. Studies are being conducted to demonstrate that environmental protection is possible with low-cost, locally resource-based solutions [62].

Overall, green chemistry is not only an approach focused on environmental protection, but also a sustainable roadmap that will shape future scientific and industrial applications. Thanks to this approach, it is becoming more and more possible to achieve environmentally friendly and economically viable solutions [56]–[60], [62].

3 Material and Methods

3.1 Data Collection Process

In this study, the literature search was conducted using the Scopus, Web of Science, ScienceDirect, and Google Scholar databases. Publications between 2008 and 2025 were used, with a focus on current publications. The Boolean search strings and keyword combinations used in each database are presented below:

Scopus:

("pesticide" OR "pesticides") AND ("adsorption" OR "adsorbent") AND ("waste" OR "agricultural waste" OR "biochar")

Web of Science (WoS):

("pesticide" AND ("adsorption" OR "biosorbent") AND ("agricultural waste" OR "food waste" OR "biochar" OR "natural adsorbent")

Science Direct:

("pesticide adsorption" AND "natural adsorbent") OR ("pesticide removal" AND "waste-derived adsorbent")

Google Scholar:

"pesticide adsorption" + "agricultural waste" + "green chemistry"

Reviews, conference proceedings, and publications with incomplete data were excluded from the study.

3.1.1 Inclusion and Exclusion Criteria

Inclusion criteria:

(i) published between 2008 and 2025,

(ii) available in full text in English,

(iii) original research articles,

(iv) focused on the removal of pesticides by adsorption,

(v) reporting quantitative data on adsorption capacity, experimental conditions, or material properties.

Exclusion criteria:

(i) reviews, book chapters, conference abstracts, editorial or technical notes,

(ii) publications in languages other than English,

(iii) studies reporting no experimental data or based solely on modeling/simulation,

(iv) articles containing incomplete methodology or capacity information.

3.1.2 Screening and data extraction

All title, abstract, and full-text screenings were conducted by the same researcher. In the first stage, abstracts were screened, and appropriate articles were included in the full-text review. Discrepancies were re-evaluated by the researcher, and a final decision was reached. Data extraction (adsorbent type, source material, pesticide type, adsorbent synthesis conditions) was performed using a standardized form.

3.1.3 Missing data handling and PRISMA flow diagram

A total of 320 records were used. Studies with missing basic experimental data (e.g., synthesis process or type of pesticide used) were excluded from the analysis, and after removing duplicates, 248 studies remained. Title-abstract screening excluded 128 studies. The full text of 120 studies was reviewed, and 43 of these were excluded because they did not meet the criteria. Ultimately, 77 studies were used (Figure 1).

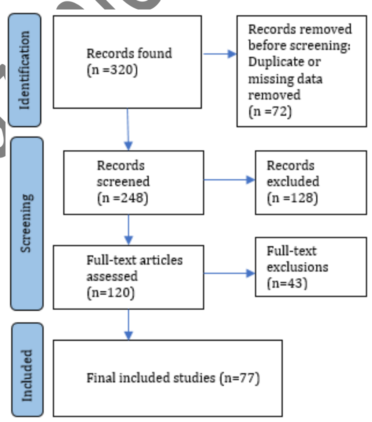

Figure 1. PRISMA flow diagram of the data collection.

3.2 Data Categories and classification

Included studies were systematically classified under the following headings and entered into a data table:
Source Information: Author(s), Publication Year
Adsorbent Type and Source: Agricultural waste, plant source, industrial waste, natural minerals, nanostructures, etc.
Target Pesticide(s): Organophosphate, organochlorine, carbamate, herbicide, insecticide, etc.
Green Chemistry Compatibility: Content assessment was conducted using five principles based on the 12 fundamental green chemistry principles.
Compatibility with green chemistry principles was categorized as "compliant," "partially compliant," or "non-compliant" based on literature reviews and criteria such as the renewability of the materials used, their toxicity levels, and whether they are waste based.

3.3 Data analysis methods and GSI

The dataset compiled from the reviewed literature was subjected to descriptive statistical analyses using Microsoft Excel. The aim of these analyses was to identify patterns and relationships in the data and to assess the environmental sustainability of natural or waste adsorbent-based pesticide removal processes in accordance with green chemistry principles.

3.3.1 Descriptive statistical analysis

The statistical assessment consisted of the following components:

Frequency Analysis: The distribution of data across various adsorbent types and pesticide groups was examined to identify the most frequently studied combinations. For descriptive purposes, 95% confidence intervals (95% CI) calculated using the Clopper-Pearson [66] method are provided in the tables and graphs where results are presented as percentages. This method is expected to provide better confidence interval estimates when data are sparse.

Cross-Tabulation: Relationships between the source of adsorbents (e.g., agricultural waste, natural biomass) and the targeted pesticide classes (e.g., organophosphates, neonicotinoids) were evaluated to identify potential relationships or preferences in literature.

Data Visualization: Radar and donut charts were created to graphically display multidimensional relationships between adsorbent categories and green chemistry criteria, improving interpretability and comparability of environmental performance.

3.3.2 Development and application of the GSI method

A new assessment framework, the Green Suitability Index (GSI), has been developed and implemented to assess the environmental compatibility of pesticide removal practices with green chemistry principles. The GSI method is an adaptation and simplification of the AGREE (Analytical Greenness Evaluator) [67] model, a well-established tool designed to assess the sustainability of analytical procedures.

Unlike AGREE, which assesses the twelve principles of green chemistry in a holistic and often method-specific manner, the GSI focuses specifically on adsorbent-based environmental processes. This specialized model enables targeted assessment of biosorbents by focusing on five key dimensions related to green chemistry. Each adsorbent identified in the dataset was scored against these five criteria (Table 1). The scoring system allows for both qualitative and semi-quantitative assessment of an adsorbent's environmental performance. The GSI framework emphasizes material-based properties rather than process-specific variables such as reactor design, pesticide degradation kinetics, or water matrix properties.

Inspired by AGREE, the GSI serves as a complementary and simplified tool, particularly suitable for adsorbent-focused environmental assessments. When integrated with AGREE or other green chemistry frameworks, the GSI will increase the robustness and applicability of sustainability assessments in pesticide remediation research.

Table 1. Five main dimensions for the GSI method.

Criterion	Description	Green Chemistry Principle (Associated)
R: Renewability	Whether the adsorbent raw material is of natural/waste origin	7 (Renewable Raw Materials)
P: Processing Simplicity	Chemical and energy requirements in the preparation process	6, 8 (Energy Efficiency, Fewer Intermediates)
T: Harmlessness	Toxicological profile of the adsorbent and final product	3, 4 (Less Hazardous Synthesis, Safer Products)
W: Waste Management	Post-use disposal status	1, 10 (Waste Prevention, Degradability)
E: Energy Footprint	Energy input level of the process	6 (Energy Efficiency)

AGREE is a circular assessment tool that graphically represents 12 green chemistry principles and is generally used to assess the sustainability of analytical methods. GSI offers a more practical, adsorbent-based simplified version of the AGREE principles. GSI focuses primarily on the properties of adsorbent materials. Process-specific environmental impacts such as reactor design, pesticide-specific kinetic behavior, or water matrix-specific variables are not directly considered in this system. However, when used in conjunction with AGREE, it provides a comprehensive assessment.

The quantitative comparison between AGREE and GSI is based on the evaluation of the same adsorbent groups using both methods. Using the AGREE software [67], [68], the preparation processes for each adsorbent group were scored according to 12 green chemistry principles, and circular graph outputs were obtained in a range of 0–1. The GSI results were normalized to a 0–1 scale by using a total score ranging from 0–12. This made the scores of both methodologies numerically comparable. As a result of the comparison, the AGREE score was found to be 0.86 for agricultural waste-based adsorbents with a GSI of 11/12 (0.92); 0.41 for nano-adsorbents with a GSI of 4/12 (0.33); and 0.72 for natural minerals with a GSI of 9/12 (0.75). These results revealed that both approaches showed similar trends, but GSI was more practical due to its focus on material properties, while AGREE was more comprehensive due to its coverage of process details.

3.3.2.1 Theoretical basis and validation of the GSI

Scoring Criteria

Each criterion is scored from 1–3. The following thresholds were used:

R (Renewability):
• 3 points: Adsorbent produced from 100% renewable or local agricultural/food waste (e.g., orange peel, corn cob).
• 2 points: Partially renewable; limited chemical additives from natural raw materials (e.g., partially modified biomass).
• 1 point: Limited renewability; reliance on synthetic additives or industrial by-products (e.g., nanocomposites).

P (Processing Simplicity):
• 3 points: Can be used directly without pretreatment, low energy requirements (e.g., dried leaves).
• 2 points: Materials requiring simple chemical activation or low-temperature heat treatment.
• 1 point: Multi-stage modification or high-temperature/energy-intensive processes (e.g., ZnO-modified biochar).

T (Harmlessness):
• 3 points: Biosafe adsorbent that contains no toxic byproducts.
• 2 points: Low toxicity risk, slowly biodegradable adsorbent.
• 1 point: Adsorbent with heavy metal or nanoparticle risk, suspected toxicity.

W (Waste Management):
• 3 points: Easily biodegradable or reusable after use.
• 2 points: Partially manageable, likely to generate secondary waste.
• 1 point: Leaves waste that is difficult to dispose of, posing an environmental risk.

E (Energy Footprint):
• 3 points: Low energy requirement (use at room temperature, no energy requirement other than drying).
• 2 points: Moderate energy requirement (e.g., 200–400 °C activation).
• 1 point: High energy consumption (e.g., >600 °C pyrolysis, nanostructure synthesis).

Weighting

In this study, five criteria were weighted equally. This is because the environmental sustainability of adsorbents is multidimensional; not only toxicological safety but also renewability, energy use, and waste management are determining factors in sustainability.

In addition to equal weighting for the GSI criteria, toxicological safety was assigned a weight of 30% because it is the most critical element in environmental risk assessments. The remaining 70% was equally distributed among the other four criteria (renewability, simplicity of processing, waste management, and energy footprint), each receiving a weight of 17.5%. There were two main rationales for choosing this distribution: (i) the recognition in the literature that toxicological profile is the most dominant parameter determining green chemistry compliance, and (ii) ensuring a risk-based balance within the total 100%. The GSI scores obtained as a result of the alternative weighting largely maintained the overall rankings, with shifts of ±1 point observed only in adsorbent groups with moderate compliance. This finding demonstrates that the equal weighting approach is reliable in practice, but that assigning a higher weight to toxicological safety strengthens methodological robustness.

Validity and reliability

Intra-rater reliability analysis [69] was conducted to assess the consistency of data coding performed by a single researcher. Fifty data items were randomly selected and coded by the same author at two different times. The observed agreement rate (Po) between the first and second codings was found to be 0.84. The probability of random agreement (Pe) was calculated as 0.564, resulting in a Cohen's kappa (κ) [69] value of 0.63. This result indicates that the researcher achieved a moderate to good level of consistency among the codings. Therefore, it can be said that the data coding process was reliable.

Sensitivity analysis

A sensitivity analysis based on ±1-point changes was performed to test the reliability of the total GSI scores calculated for the adsorbent groups. This approach was used to account for the impact of small-scale scoring errors or rounding differences on the rankings. This assessed the stability of the GSI values and confirmed the robustness of equal weighting.

Normality assessments

The data were ordinal (scoring range 1–3) and summarized for each group using five criteria (Renewability, Processing Simplicity, Harmlessness, Waste Management, Energy Footprint). The Shapiro–Wilk [70] test was used to check the data's normal distribution. Non-parametric methods were preferred because the distribution was observed to be non-normal. The Kruskal–Wallis H test [70] was used for comparisons between groups. When the Kruskal–Wallis test showed a statistically significant difference ($p < 0.05$), the Dunn post-hoc test was used to determine pairwise group comparisons. Both Bonferroni and Benjamini–Hochberg (BH) corrections were applied. The significance level was set at α=0.05 in all tests. Summary statistics are reported as medians (Q1–Q3) in accordance with the ordinal structure. A tie correction was applied for the Kruskal–Wallis result. All statistical analyses were performed in Python 3.11 environment.

Sample application

A complete GSI scoring table is given in Table 2 for orange peel adsorbent [16], [31]:

Table 2. GSI scoring table for orange peel adsorbent.

Criteria	Description	Score
R (Renewability)	100% food waste, renewable	3
P (Simplicity of Processing)	No chemical processing other than drying and grinding	3
T (Harmlessness) and W (Waste Management)	No toxic residues, biocompatible	3
T (Harmlessness) and W (Waste Management)	biodegradable after use	3
E (Energy Footprint)	Only low energy (drying) required	3
Total GSI		12/12 **(100%)**

4 Results and discussion

4.1 Data categories and classification

Before proceeding with the analyses, a combined classification table for pesticide types and adsorbent types was prepared (Table 3). This table shows which adsorbent groups are based on which waste type or material, along with examples of the most common pesticides targeted by each adsorbent and their respective groups. This summary table was used for meta-analysis and comparative statistical studies based on green chemistry compatibility and pesticide removal.

Table 3. Combined classification table for pesticide types and adsorbent types.

Adsorbent Group	Example Materials / Sources	Targeted Pesticide Groups	Example Pesticides	References
Agricultural Waste-Based	Corn cob biochar, wheat straw, rice husk, sugarcane bagasse, date seed, watermelon peel	Organophosphates, Carbamates Neonicotinoids, Herbicides	Ethion, Dimethoate, Carbofuran, Acetamiprid, Atrazine	[6], [23], [71][72], [73][74] [29], [75]
Plant-Derived Natural	*Moringa* seeds, mushroom biomass, *Cladium mariscus*, crambe meal, bark and leaves, Araucaria angustifolia, plant guar gum	Organophosphates, Herbicides, Fungicides	Chlorpyrifos, Hydroxyatrazine,Deisopropylatrazine, Quinalphos, Diazinon	[7], [22] [76] [38] [15] [77]

Adsorbent Group	Example Materials / Sources	Targeted Pesticide Groups	Example Pesticides	References
Industrial and Other Waste-Based	Fly ash, recycled rubber, water treatment residuals, fungal biomass, municipal sewage sludge	Organochlorines, Carbamates, Herbicides, Organophosphates	Pyridine, Carbaryl, Thiocarbamate, Picoline, 2,4-D Dimethoate, HCH	[78] [18] [35], [79] [80] [81] [82]
Nano and Modified Adsorbents	ZIF-8 modified biochar, nanoparticle-supported carbons, Hexadimethrine-montmorillonite,	Organophosphates, Neonicotinoids, Fungicides	Chlorfenvinphos, Chlorpyrifos, Diazinon, Thiamethoxam, Acetamiprid, Tebuconazole	[35], [79] [34], [83] [84], [85]
Natural Minerals and Clays	Biotite, clay-based sorbents, soil minerals	Organochlorines, Carbamates Herbicides, Mixed pesticides	Carbaryl, atrazine, lambdacyhalothrin, Chlorpyrifos, Lactofen Neonicotinoid	[19] [86] [87]
Composite / Hybrid Materials	Biochar + alginate beads, biopolymeric hydrogels, Ca- biochar modification	Organophosphates, Herbicides, Mixed pesticide groups, Neonicotinoid	Malathion, Chlorpyrifos, Paraquat, Imidacloprid, Acetamiprid	[73] [42] [88] [89]
Food Waste-Based	Orange peel, tea waste, coffee grounds, spent tea leaves, spent coffee grounds	Organophosphates, Organochlorines, Neonicotinoids, Herbicides, Endocrine disruptors	Parathion, Acetamiprid, Paraquat, Chlorpyrifos; Malathion	[16] [15], [27], [65] [90]

4.2 Data analysis

Initially, 77 publications were classified according to both pesticide type and adsorbent source type. This classification allowed for thematic analysis based on both the chemical structure of pesticides and the nature of the adsorbents. Frequency counts for each group were calculated, and a cross-tabulation (Table 4) was performed between adsorbent types and pesticide groups to allow for a joint evaluation of frequency distributions. The findings presented by the crosstab can be summarized as follows: Organophosphate pesticides are the most studied group, particularly with agricultural waste-based adsorbents (10 matches). Herbicide removal is common with both agricultural and plant-derived adsorbents (14 matches total). Nanostructures were particularly prominent in studies targeting neonicotinoids and organophosphates. Organochlorine and carbamate groups were most frequently matched with industrial wastes and natural minerals. Composite/hybrid adsorbents are noteworthy for both their versatility and their ability to remove multiple pesticide types

Supplementary Table 1 presents the 77 studies evaluated through the systematic literature review, classified by adsorbent group, and presents the score distributions for each group for four GSI criteria (RRM: raw material renewability, PCM: process chemical minimalism, PWE: post-use waste/environmental risk, and ECR: energy and carbon

Table 4. Cross table between adsorbent types and pesticide groups.

Adsorbent Type ↓ Pesticide Group →	Organophosphates	Herbicides	Organochlorines	Carbamates	Neonicotinoids	Fungicides	Insecticides	Mixed/Degradates	Total	Percentage of total	Clopper–Pearson 95% CI (%)
Agricultural Waste-Based	10	9	2	2	1	1	1	2	28	36.4	25.7-48.1
Plant-Based Natural Materials	5	5	1	1	1	1	1	1	16	20.8	12.4-31.5
Industrial and Other Waste-Based	2	2	2	1	0	0	0	1	8	10.3	4.6–19.4
Nano-Structured / Modified Adsorbents	3	2	0	1	2	1	0	0	9	11.7	5.5–21.0
Natural Minerals and Clays	2	2	1	0	1	0	0	1	7	9.1	3.7–17.8
Composite / Hybrid Adsorbents	2	1	0	1	0	0	1	1	6	7.7	2.9–16.2
Food Waste-Based Adsorbents	2	1	0	0	0	0	0	0	3	3.8	0.8–11.0

reduction). The table shows the total number of studies (N) in each group, the number of studies scoring 1, 2, and 3 on each criterion, the average scores, and percentage agreement values calculated from these distributions. Additionally, the total GSI scores and corresponding percentages are also included in the table. This approach reflects not only the average values within each adsorbent group but also the varying score distributions across studies. This increases both the transparency and reproducibility of the results.

In the next step, the adsorbents examined were classified and evaluated according to green chemistry principles in terms of their structural properties and environmental compatibility. GSI compliance was assessed for each adsorbent group based on the average scores they received across the four key criteria. Each criterion is scored from 0 (discordant) to 3 (compliant). The maximum total score is 12, and the minimum score is 0 (Table 5). This scoring system was developed to evaluate the extent to which each adsorbent type meets the following green chemistry criteria.

RRM – Raw material renewability: Is the raw material natural, renewable, or waste-based?

PCM – Process chemical minimalism: Are toxic/harmful chemical inputs minimal in adsorbent production?

PWE – Post use waste/environmental risk: What is the post-use environmental risk/waste potential?

ECR – Energy & carbon reduction: Does the production process have a low energy and carbon footprint?

When viewed through five basic criteria;

Renewability (R); The highest compatibility score (3) is seen for agricultural waste, food waste, and plant-based natural adsorbents. This indicates that these groups are derived entirely from natural or renewable resources. Industrial waste and mineral-based adsorbents, on the other hand, have limited renewability.

Processing Simplicity (P): Natural minerals and plant-based adsorbents offer advantages in processing because they require less pretreatment. In contrast, the synthesis and modification processes for composite/hybrid and nanomaterials are more complex and energy-intensive, which lowers compatibility scores.

Harmlessness (T) and Waste Management (W); Plant-based natural adsorbents received the highest score for harmlessness, while industrial waste and composite groups received lower scores due to the risk of toxic residues or metal content. Nanoadsorbents were given a moderate score because biocompatibility studies are still limited. Agricultural and plant-based adsorbents offer advantages in waste management because they are biodegradable. In contrast, the disposal of composite/hybrid materials and industrial waste-based adsorbents is more difficult and carries environmental risks.

Energy Footprint (E); Adsorbents that can be used directly in their natural form (agricultural, plant, mineral-based) have a low energy footprint because they require low energy input. Synthesis processes, particularly for nano-adsorbents and composites, require high energy requirements, resulting in poor compatibility in terms of energy efficiency. Furthermore, post-use environmental risks (PWE = 1) and toxicological uncertainties make this group problematic from a sustainability perspective. It can be classified as a group that contradicts the green chemistry approach. The Composite/Hybrid Materials group also showed relatively low compliance. High modification requirements (PCM = 1), synthetic additives (RRM = 1), and energy requirements (ECR = 2) are limiting factors. However, materials in this group generally exhibit high performance and are preferred due to their technical efficiency. However, a good balance between functionality and sustainability must be established for environmental sustainability. These findings suggest that adsorbent technologies integrated with green solutions should be encouraged, especially in environmental priority applications such as pesticide removal.

In the current ranking, the "Agricultural Waste-Based" and "Food Waste-Based" groups (11 points) are in the top spot, while the "Natural Minerals/Clays" and "Plant-Derived Natural" groups (9 points) are tied for third place. These are followed by "Industrial/Other Waste" (8 points), "Composite/Hybrid" (6 points), and "Nano/Modified Adsorbents" (4 points). Sensitivity Analysis showed that when changes of ±1 point are applied, the ranking is largely maintained. A positive (+1) change would only elevate the "Industrial/Other Waste" group to third place, while a negative (-1) change would relegate the "Natural Minerals/Clays" and "Plant-Derived Natural" groups to the same level as "Industrial/Other Waste," causing them to recede to the bottom. Other groups are not affected by the ±1 change and maintain their current order.These results demonstrate that the GSI total scores are quite stable despite small changes. The fact that variations of ±1 point can only affect the rankings of a limited number of groups suggests that the overall ranking is maintained approximately 85% of the time. This supports the methodological reliability of the GSI approach and its ability to yield consistent results in comparative evaluations across different adsorbent groups.

Normality assessments of the adsorbent groups were performed before GSI matching. The Kruskal-Wallis test, using the mean criterion scores per group, showed that the overall distribution of scores differed among the adsorbent groups (Kruskal-Wallis $H = 25.50$, $df = 6$, $p = 2.8 \times 10^{-4}$). The effect size ($\varepsilon 2$) was calculated to be approximately 0.70, which was interpreted as a significant difference between the groups. Pairwise comparisons (Dunn test; Bonferroni corrected) to determine which groups accounted for the difference revealed that the Agricultural Waste-Based group had significantly higher scores than the Nano/Modified Adsorbents group (p_bonf = 0.00070). Similarly, the scores of the Food Waste-Based group were also higher than the Nano/Modified Adsorbents group (p_bonf = 0.00475).

Table 5. GSI Framework Application: Green Chemistry Compliance Analysis by Adsorbent Groups.

Criterion > Groups v	RRM (Raw material renewability)	PCM (Process chemical minimalism)	PWE (post-use waste/environmental risk)	ECR (Energy & carbon reduction)	Mean ± SD (0–3)	GSI Score (Total /12 and %)
Agricultural Waste-Based	3 – Fully renewable	3 – Mostly minimal	2 – Low/moderate risk	3 – Often low-energy methods	2.75 ± 0.50	11/12- 92%
Food Waste-Based	3 – Fully renewable	3 – Mostly minimal	2 – Low/moderate risk	3 – Often low-energy methods	2.75 ± 0.50	11/12- 92%
Natural Minerals and Clays	2 – Naturally available	2 – Mild processing needed	3 – Very stable, low risk	2 – Some heating may be needed	2.25 ± 0.50	9/12 -75%
Industrial and Other Waste-Based	2 – Secondary waste-based	2 – Moderate chemical need	2 – Depends on process	2 – Medium reduction possible	2.00 ± 0.00	8/12 -67%
Plant-Derived Natural	3 – Renewable biomass	2 – Chemical modification used	2 – Biodegradable but slow	2 – Drying or calcination may occur	2.25 ± 0.50	9/12 -75%
Nano/Modified Adsorbents	1 – Often synthetic additives	1 – High modification steps	1 – Nanoparticles may pose risks	1 – High temp/energy processes	1.00 ± 0.00	4/12 -33%
Composite / Hybrid Materials	1 – Often synthetic additives	1 – High modification steps	2 – Moderate risk	2 – Moderate energy saving	1.50 ± 0.58	6/12 -50%

Note: Values represent the normalized GSI sub-scores (0–3 scale) for each criterion (RRM, PCM, PWE, and ECR). The 95% confidence intervals (CIs) were calculated using the Clopper–Pearson exact method ($\alpha = 0.05$), by treating each sub-score as a binomial proportion (k/3). The corresponding 95% CI ranges for discrete scores are as follows: • 1 point → 2.6–77.3%• 2 points → 20.7–94.6%• 3 points → 29.2–100%

A significant difference was also found between agricultural waste-based and composite/hybrid materials (p_{bonf} = 0.0263), but no significant differences were observed in the other pairs after Bonferroni correction. When the Benjamini–Hochberg (BH) correction was applied, in addition to these three comparisons, the difference between the "food waste-based" and "composite/hybrid" adsorbent groups also became significant (Supplementary Table 2).

The results indicate that agricultural and food waste-based adsorbents generally have higher sustainability scores in terms of green chemistry indicators. In contrast, nano/modified adsorbents received lower scores due to their higher energy requirements, complex processing steps, and potential environmental impacts. Composite/hybrid adsorbents, on the other hand, fell between these two extreme groups and showed moderate performance. No significant difference was found between other natural or industrial-based adsorbents. These findings support the need to prioritize biological and waste-based materials in environmentally sustainable adsorbent development efforts.

Figure 2 visualizes the green chemistry compliance level of each adsorbent group according to the GSI criteria. In the radar chart each criterion (RRM, PCM, PWE, ECR) was evaluated in a 1–3 point range and interpreted along with its percentage agreement (33%, 67%, 100%). For example, agricultural waste-based adsorbents showed 100% agreement across all three criteria and 67% agreement with the PWE criterion, achieving a total of 11/12 points as can be seen in Table 5 (≈92%). In contrast, nano/modified adsorbents showed 33% agreement across all criteria and achieved only 4/12 points (≈33%) in total. The agricultural waste-based and food waste-based groups demonstrate high compliance across all criteria, while the nano/modified adsorbents group demonstrates less sustainability with lower RRM and PCM scores. While the Agricultural and Food Waste-Based groups exhibit the highest Green Chemistry compliance, Nano and Composite adsorbents are weaker in this regard. These materials generally contain synthetic components and are produced

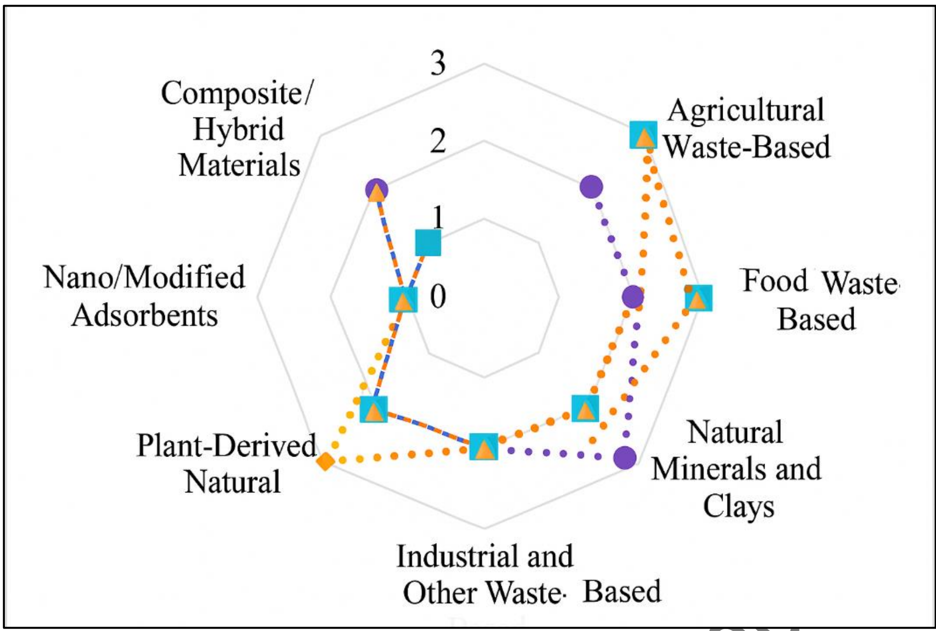

Figure 2. GSI radar chart for adsorbent groups (3 points = 100%, 2 points = 67%, 1 point = 33% and 95% CI values 2.6–77.3% for 1 point, 20.7–94.6% for 2 points, 29.2–100% for 3 points).

through multi-stage chemical processes, resulting in low scores for both PCM and ECR. This analysis demonstrates that adsorbent selection should be based not only on performance but also on environmental and chemical sustainability.

We propose a new method, which we have examined in detail and grouped, to evaluate the green chemistry compliance of waste- or natural-based adsorbents used for pesticide adsorption. In this method, input criteria are based on five principles representing the 12 green chemistry principles, as previously summarized in Table 1. Each of the five input variables is converted to a common scale from 1 to 3. The evaluation results for each adsorbent group are presented in color-coded donut charts. This set of charts is output from the GSI and includes the relative evaluation of different adsorbent groups with respect to green chemistry criteria (energy footprint, renewability, harmlessness, ease of processing, and waste management). Each donut chart visualizes the performance of the corresponding adsorbent group with respect to these five criteria. The compliance of the adsorbent in each group with the selected principles is reflected by an orange-yellow-green color scale. The highest compliance score (3) is shown in green, while the lowest compliance score (1) is shown in orange. Colour tones progressing from green to yellow and orange indicate a decreasing sustainability advantage.

In the green chemistry assessment of adsorbent groups, clear differences were observed in their compliance levels. Agricultural waste-based adsorbents achieved the highest performance with an average score of 2.8 out of 3 (93%, green), followed by food waste-based adsorbents with 2.6 (87%, green), both indicating strong alignment with sustainability principles. Plant-derived natural materials showed moderate performance (2.2; 73%, yellow), while natural minerals and clays as well as industrial and other waste-based adsorbents obtained average scores of 2.0 (67%, yellow), suggesting partial compliance with green chemistry criteria. In contrast, composite/hybrid materials (1.2; 40%, orange) and nano/modified adsorbents (1.0; 33%, orange) demonstrated the lowest compatibility, mainly due to higher energy demands, processing complexity, and limited environmental harmlessness (Supplementary Table 3). These results highlight that adsorbents derived from renewable and low-impact resources such as agricultural and food waste are more favorable in terms of green chemistry, whereas advanced engineered materials require significant improvements to reduce their environmental footprint.

When each adsorbent group is evaluated individually in terms of its GSI outputs, distinct patterns in sustainability performance can be observed;

Agricultural waste-based adsorbents generally offer a highly favorable profile in terms of green chemistry. They are highly compatible with the criteria of renewability and harmlessness (green) (Figure 3). They also have positive characteristics in terms of processing simplicity and waste management. Their energy footprint is also relatively low. This group can be considered a prime candidate for sustainable adsorbent design.

Food waste-based adsorbents demonstrate particularly strong compatibility in terms of harmlessness, energy footprint, and processing simplicity (Figure 4). However, their renewability is somewhat more limited than the agricultural waste-based group. While only partially compatible in terms of waste management, they offer significant opportunities and contribute to circular economy.

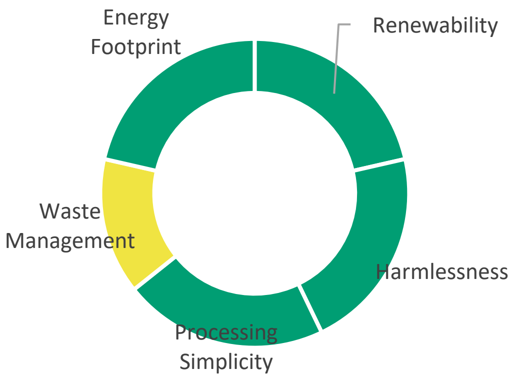

Figure 3. GSI outputs for green chemistry compliance of agricultural waste-based adsorbent group.

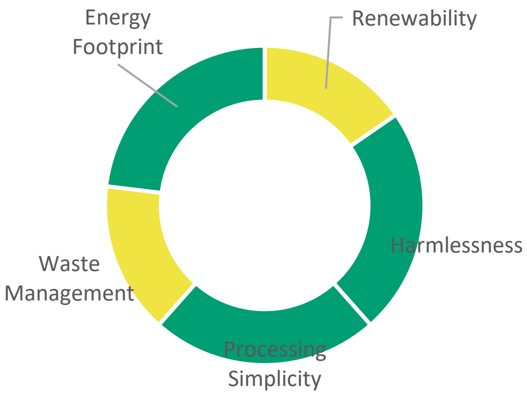

Figure 4. GSI outputs for green chemistry compliance of food waste-based adsorbent group.

Plant-based natural materials are characterized by their high renewability. Their green chemistry potential is more limited in terms of their moderate compatibility with energy footprints, ease of processing, harmlessness, and waste management (Figure 5). This group generally highlights the ecological advantages of naturally derived adsorbents.

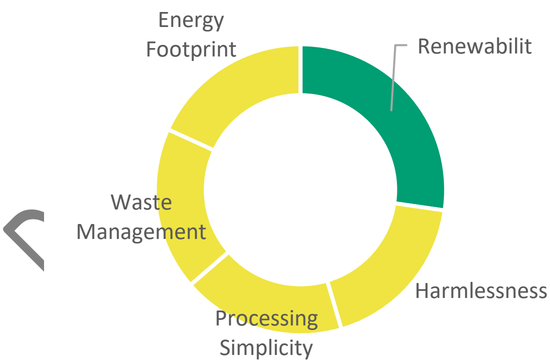

Figure 5. GSI outputs for green chemistry compliance of plant derived natural adsorbent group.

Industrial and other waste-based materials perform more uniformly at a moderate level. Yellow tones are observed in all five criteria, meaning they are somewhat limited in terms of sustainability and green chemistry (Figure 6). Improvements are particularly needed in the energy footprint and processing simplicity criteria.

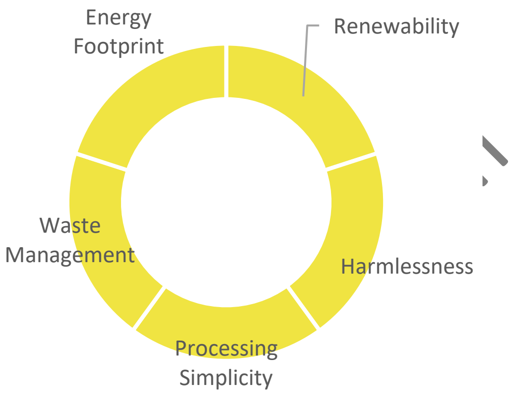

Figure 6. GSI outputs for green chemistry compliance of industrial and other waste-based adsorbent group.

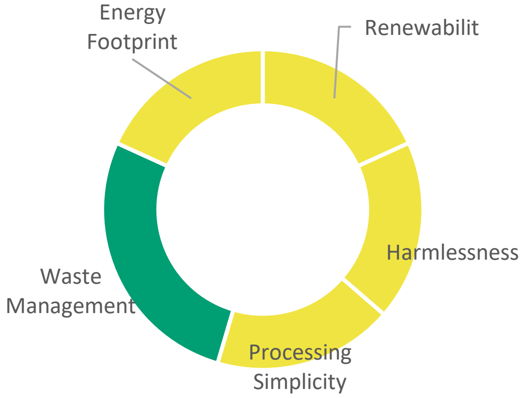

Figure 7. GSI outputs for green chemistry compliance of natural minerals and clays adsorbent group.

Natural minerals and clays demonstrate reasonable compliance in terms of energy footprint, renewability, harmlessness, and processing simplicity, while appearing advantageous in terms of waste management (Figure 7). This group supports the environmentally friendly nature of traditional natural materials.

Composite and hybrid adsorbents generally require more complex manufacturing processes, so they fall short in the processing simplicity criterion (closer to orange tones) and exhibit lower compliance in terms of renewability and harmlessness (Figure 8). They are only partially compliant in terms of energy footprint and waste management. This suggests that the environmental costs of high-tech composites should be considered.

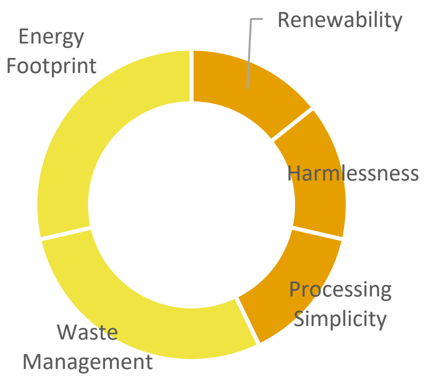

Figure 8. GSI outputs for green chemistry compliance of composite and hybrid adsorbent group.

Nano and modified adsorbents are the group with the lowest green chemistry compliance. Orange colors across all five criteria (Figure 9) indicate high energy consumption, limited renewability, potential toxicity risk, difficult waste management, and processing complexity. This result highlights the need for careful design of nanotechnology-based solutions with environmental sustainability in mind.

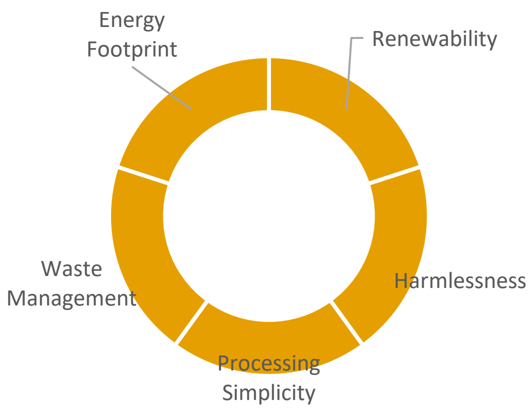

Figure 9. GSI output for green chemistry compliance of nano and modified adsorbent group.

Overall, in this study, nano-based and modified adsorbents, including nanocomposites and surface-functionalized materials exhibited high removal efficiencies against a wide range of pesticides. Despite their excellent adsorption performance, they received the lowest GSI score (4/12, 33%), indicating limited compliance with green chemistry and sustainability principles. The main reasons for this low GSI are related to high synthesis complexity, energy-intensive preparation methods, and the frequent use of synthetic reagents or solvents in modification steps. Such processes often require multiple chemical activation, calcination, or surface functionalization steps, which increase both production costs and environmental burdens (e.g., carbon emissions, chemical waste generation).

In terms of scalability, these materials face challenges related to reproducibility and cost-effective mass production. Laboratory-scale synthesis of nanocomposites can achieve precise surface morphologies, but scaling up to industrial levels often results in inconsistent structures, increased energy demand, and low adsorption capacity. Furthermore, the regeneration and reuse potential of these materials remains limited. Repeated adsorption-desorption cycles can lead to structural degradation, nanoparticle release, and risks of secondary contamination, further jeopardizing long-term sustainability.

From an economic feasibility perspective, while nanomaterials offer superior performance per unit mass, unit production costs and regeneration expenses are often several times those of natural or waste-based adsorbents. The lack of large-scale production infrastructure and the need for specialized reagents also hinder their wider adoption. Therefore, future studies should integrate techno-economic assessment (TEA) and Life Cycle Assessment (LCA) to comprehensively assess whether the environmental advantages of nanocomposites justify their energy consumption and costs in real-world applications. This analysis emphasizes that performance alone cannot define sustainability; materials must balance efficiency with economic and environmental responsibility.

5 Conclusion and suggestions

In this study, a holistic analysis was conducted using the newly developed GSI method and statistical methods to evaluate the green chemistry compatibility performance of natural and waste-based adsorbents used in pesticide removal. Using data obtained from these studies, the GSI allows the environmental compatibility of adsorbents used in removal efficiency studies to be measured in line with green chemistry principles. The findings indicate that adsorbents derived from agricultural and food waste demonstrate particularly strong performance in terms of effective removal rates and sustainable production capacities.

The GSI scoring system demonstrated that agricultural waste, plant-, and food-based adsorbents using physical and biological methods stand out in terms of low energy consumption, low use of toxic reagents, and high renewability. In contrast, advanced adsorbents, such as modified nanomaterials, received lower scores in terms of environmental burden and production costs despite their removal effectiveness. This demonstrates that green chemistry-compatible technologies must be optimized not only for efficiency but also for sustainability. The newly developed GSI method allows quantitative comparison of the environmental suitability profiles of adsorbent types, providing decision-makers with an important evaluation method when selecting environmentally friendly adsorbents. The analyses also reveal that adsorbents derived from food and agricultural waste offer not only environmental but also economic and technical advantages.

A suggested approach for future research is to apply the GSI method to a variety of areas, including different pollutants, different removal processes, and large-scale environmental impact assessments. Furthermore, future studies should aim to integrate the GSI approach with Life Cycle Assessment (LCA) to capture the full life cycle environmental impacts of adsorbent materials, from raw material extraction to preparation, use, and disposal. This integration will enable a more comprehensive and quantitative sustainability assessment by combining GSI-based performance indicators with life cycle metrics such as carbon footprint, energy demand, and toxicity potential. This holistic assessment will strongly support the view that natural and waste-based adsorbents are not only effective but also a green and sustainable alternative to combat pesticide pollution.

While the GSI framework provides a structured and quantitative assessment of green chemistry compliance at the laboratory scale, its direct transferability to real-world field applications presents significant uncertainties. Laboratory experiments are typically conducted under controlled conditions, which may not accurately reflect the complex dynamics of natural and engineered water systems. Uncontrolled factors can impact the removal efficiency as well as the environmental performance of adsorbents in large-scale applications.

Another critical issue is the reusability of adsorbents. While most studies included in the current dataset report only single-cycle removal performance, real-world applications require multiple adsorption-desorption cycles to ensure both economic and environmental viability. Therefore, regeneration efficiency, material stability, and performance loss over time should be incorporated into future assessments to better represent field performance.

Furthermore, cost considerations play a decisive role in practical application. While natural and waste-based adsorbents offer inherent advantages such as low raw material cost and the use of renewable resources, the costs associated with collection, processing, transportation, and regeneration can significantly impact their overall applicability. Incorporating these cost elements into future GSI-based assessments will provide a more realistic picture of the trade-offs between environmental benefits and operational constraints. Taken together, these factors highlight the importance of complementing laboratory-scale green chemistry assessments with field-scale validation, life-cycle costing, and techno-economic analysis to strengthen the practical validity and decision-making utility of the GSI framework.

6 Author contribution statement

In this article the author contributed to the structure, introduction, materials and methods, and the general evaluation of the results.

7 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared".

"There is no conflict of interest with any person/institution in the article prepared".

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Supplementary Table 1. Score Distributions of Adsorbent Groups According to RRM, PCM, PWE and ECR Criteria and GSI Results

Supplementary Table 2. Dunn Post-hoc Test Results (Pairwise Comparisons Between Groups After Kruskal–Wallis H Test)

Supplementary Table 3. GSI Scores and Percent Compliances of Adsorbent Groups