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Adsorbents Derived from Plant Sources for Caffeine Removal: Current Research and Future Outlook

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INTRODUCTION & AIM

Pharmaceutical and personal care products (PPCPs), like caffeine, are emerging contaminants in water bodies, posing risks to human and environmental health. Caffeine, found in coffee, tea, and cacao, boosts alertness by blocking adenosine receptors but is not fully metabolized, leading to its presence in wastewater and aquatic ecosystems. This contamination disrupts marine and coastal species' growth, reproduction, and metabolism. Conventional wastewater treatment plants (WWTPs) struggle to remove caffeine, necessitating alternative methods. Adsorption using activated carbon (AC) is effective but costly, prompting exploration of cheaper, sustainable plant-based adsorbents. This study evaluates plant-based adsorbents for caffeine removal, focusing on specific surface area, adsorbent dosage, pH level, maximum adsorption capacity, adsorption isotherms, and kinetics.

METHOD

A systematic literature review was conducted to identify research trends in caffeine adsorption using plant-derived adsorbents:

- Planning: Identified relevant keywords, selected publication dates, and used databases to filter papers automatically.
- Selection: Manually checked papers to ensure they met review criteria.
- Extraction: Employed data extraction and cross-referencing to identify patterns.
- Execution: Used the search equation "caffeine" AND "type" AND "adsorption isotherm" in ScienceDirect, interchanging "type" with terms like fruit, fiber, stalk, and others, resulting in 1946 studies.
- Filtering: Applied PRISMA guidelines, reducing 1946 studies to 66 after removing duplicates and examining titles.
- Eligibility: Assessed abstracts, leaving 17 papers for final analysis.

The review evaluated specific surface area (SSA), adsorbent dosage, pH level, maximum adsorption capacity (MAC), adsorption isotherms, and kinetics.

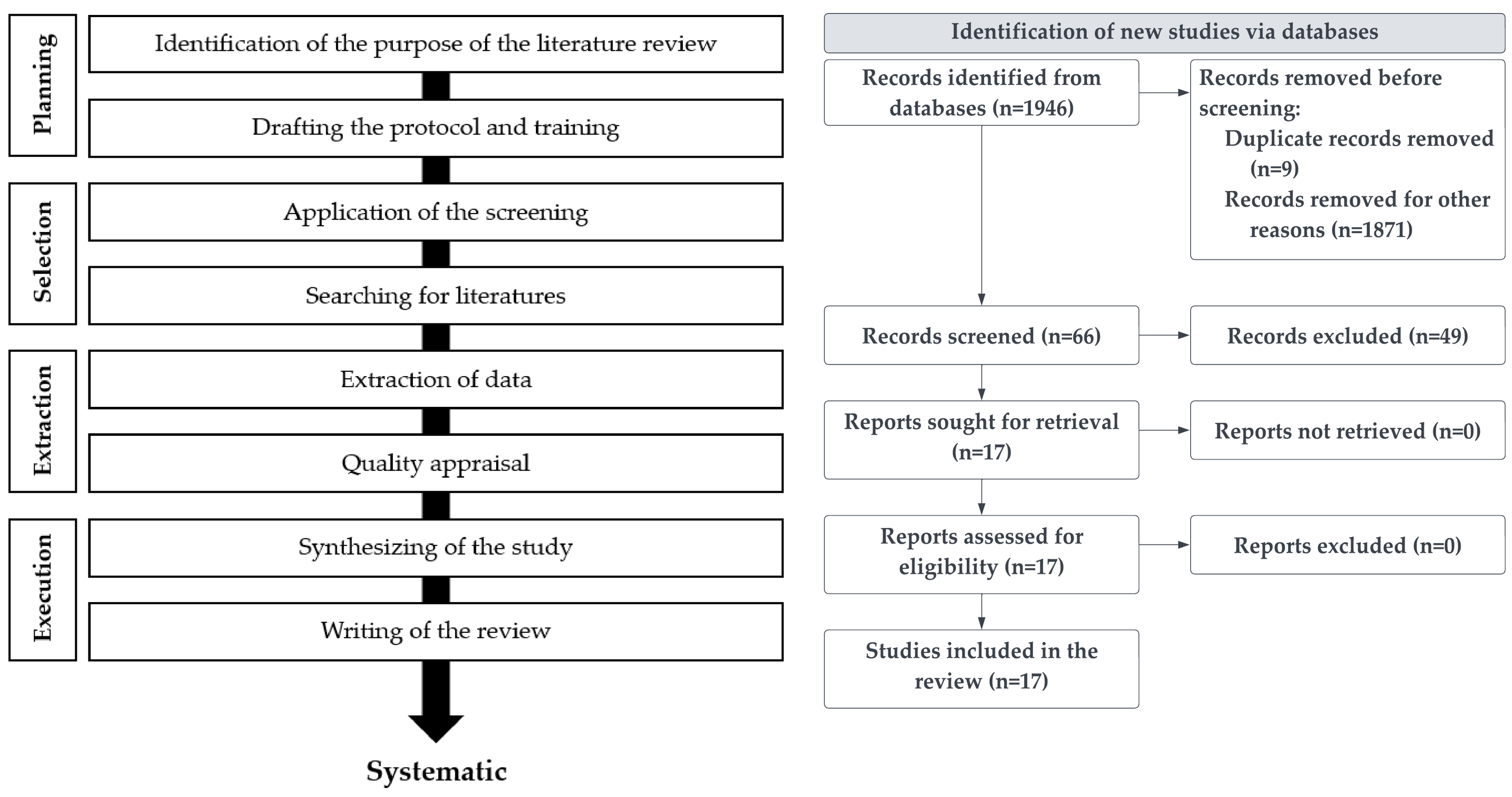

Figure 1. Adapted systems and methodologies: (a) Systematic Literature Review Adapted from Okoli (2015) [1]; (b) Adapted PRISMA Diagram from Page et al. (2021) [2].

RESULTS & DISCUSSION

The study analyzed various parameters affecting caffeine adsorption using plant-derived adsorbents:

- The average SSA was 609.65 m²/g, with 15 adsorbents below 500 m²/g also showing lower MAC.
- The highest SSA and MAC were observed in TWPC-800 and GSAC, respectively, highlighting the complexity of factors affecting adsorption beyond SSA alone.
- The average adsorbent dosage was 2.67 g/L, with GSAC demonstrating high efficiency at 1 g/L.
- The optimal pH for adsorption was found to be around 5.57, although GSAC achieved the highest MAC at pH 4.
- Langmuir and Sips isotherms were flexible across adsorbents, with pseudo-second-order kinetics describing most adsorption processes efficiently.
- GSAC, TWPC-800, and Pi/1:1/800/2, derived from grape stalks, tea wastes, and pines, respectively, showed promising results, indicating cost-effective and sustainable alternatives to commercial activated carbon.

These findings suggest potential for further research into similar natural adsorbents, advancing towards commercial application.

RESULTS & DISCUSSION

Table 1. Summary of properties of different adsorbents derived from plant sources and parameters of the adsorption process.

Adsorbent	SSA (m^2/g)	Dosage (g/L)	pH	MAC (mg/g)	Adsorption Isotherm	Adsorption Kinetics
Orange Peel	0.801	3.5	6.9	15.188	LM	PFO
Banana Peel	0.079	9.5	6.9	6.761	LM/SP	PFO
Orange Peel Composite	14.282	2.5	6.9	25.604	LM/SP	PFO
Banana Peel Composite	8.140	5.5	6.9	11.668	LM	PSO
KAC	420.46	1	7	391	FL	PSO
CAC	53.92	1	7	139.61	FL	PSO
CH-KAC	1082.41	1	7	121.9	LM	PSO
CH-CAC	240.79	1	7	39.53	LM	PSO
CA-SA 400/10	1150.3459	1	7	176.8	n/a	PSO
Pineapple ACF	1031	1	5.8	152.18	LM	PSO
Peanut shell AC	790	0.05	5	0.63 mmol/g	LM	n/a
Peanut shell AC	790	0.05	7	1.11 mmol/g	LM	n/a
GS	6.23	25	2	89.194	SP	N/A
MGS	4.21	15	2	129.568	SP	N/A
GSAC	1099.86	1	4.0	916.679	SP	N/A
NS900	167.71	0.25	7	9.24	LM	PSO
WP900	156.08	0.25	7	11.85	LM	PSO
SAC	754	0.6	6	221.61	LM	PSO
ABC	740	1	6	117.8	LM	PSO
TWBC-SA	576	1	3.5	15.4	FL	ELV
TWPC-800	2260.82	2.5	n/a	491.37	LM	PSO
CW-C-1-800	1212	0.2	5	274.2	LM	PFO/PSO
MBC1	474	1	n/a	45	SP	PSO
ACP	1242	1	n/a	259	SP	PSO
MNC	1019	1	n/a	168	SP	PSO
GBC300	1.02	1	4.5	n/a	FL/TK	ELV/FTP
GBC500	76.30	1	4.5	n/a	FL/TK	ELV/FTP
GBC700	216.40	1	4.5	16.26	FL/TK	ELV/FTP
Pi/1:1/800/2	945	6 mg	5	500	LM	PSO
Pi/1:3/800/2	1509	6 mg	5	476.2	LM	PSO
YC	823	0.6	n/a	130	SP	PSO
NP-YC	644	0.6	n/a	139	SP	PSO
OLC	n/a	1.67	4	59.88	LM	PSO

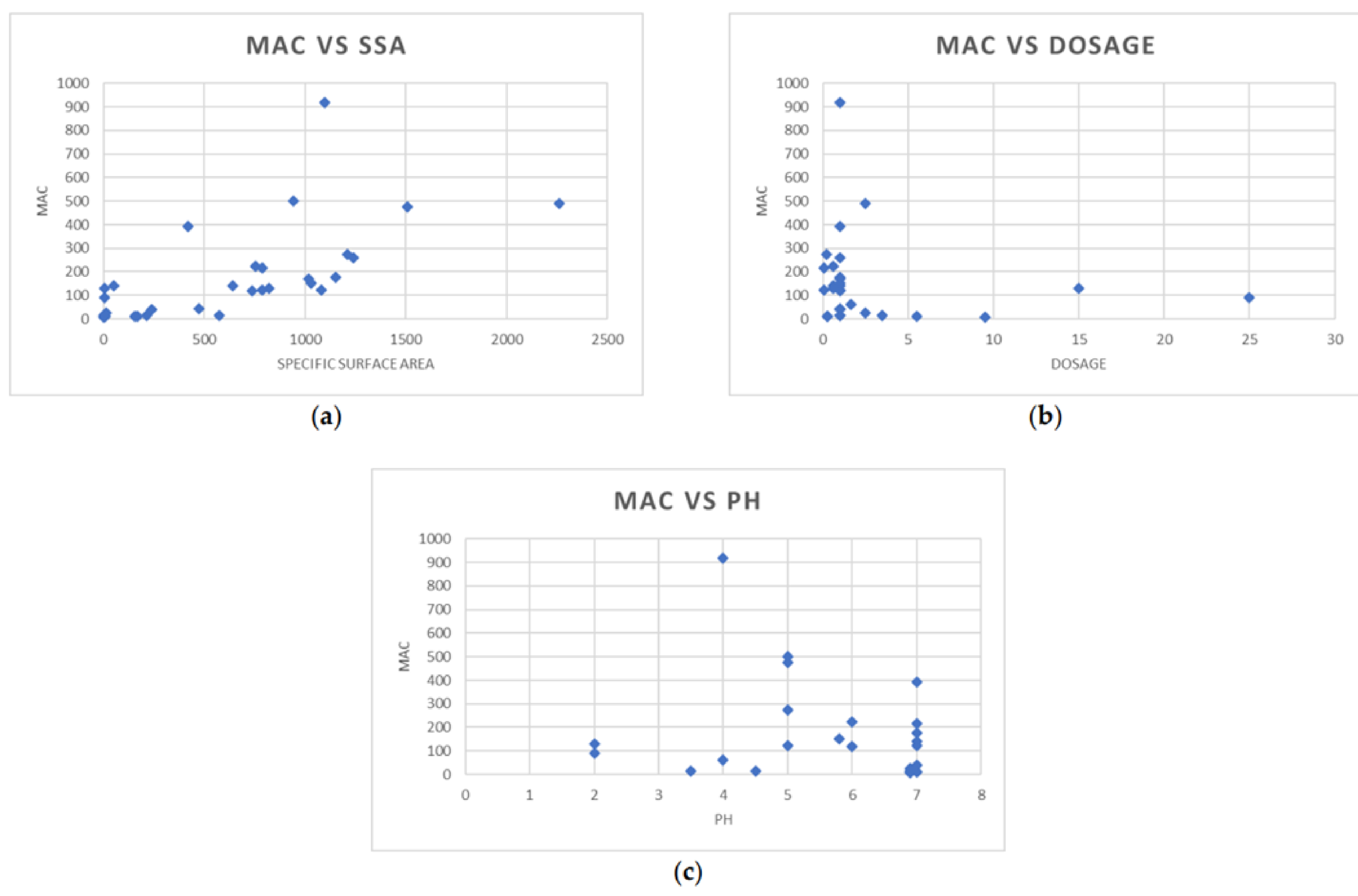

Figure 2. Adsorbents MAC against different characteristics: **(a)** MAC vs SSA; **(b)** MAC vs Dosage; **(c)** MAC vs pH.

CONCLUSION

- Optimal adsorption typically requires a low dosage and acidic conditions, though these may vary by material.
- Langmuir and Sips isotherms, along with pseudo-second-order (PSO) kinetics, effectively describe the adsorption process.
- Promising results from grape stalks, tea wastes, and pines indicate the need for further research and upscaled experiments.
- Despite current study limitations, the trend towards naturally derived adsorbents for caffeine removal is expected to grow as methods improve.

REFERENCES

[1] Okoli, C. (2015). A Guide to Conducting a Standalone Systematic Literature Review. Communications of the Association for In-formation Systems, 37. https://doi.org/10.17705/1CAIS.03743

[2] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Systematic Reviews, 10(1), 89. https://doi.org/10.1186/s13643-021-01626-4