

Systematic Hydroponic Review and Cultivation Strategies for *Bacopa Monnieri*

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Abstract

Bacopa monnieri (L.) Wettst. (Brahmi; Plantaginaceae) is a medicinally important herb whose nootropic, antioxidant and anti-inflammatory properties derive largely from a group of triterpenoid saponins known as bacosides. Rising global demand for such compounds has made reliable, high-yield production a research priority and has prompted a search for cultivation systems superior to conventional field cultivation. This review compares field cultivation, in vitro micropropagation, bioreactor culture, hydroponics and elicitation for their capacity to enhance biomass and bacoside accumulation, synthesizing the quantitative findings of fourteen primary experimental studies retrieved through a structured semantic literature search. Field cultivation is inexpensive but vulnerable to environmental variation, whereas micropropagation yields disease-free, genetically uniform plants at the cost of specialised infrastructure. Hydroponics emerged as the most promising approach; the soilless systems markedly improved biomass to greater dry weight through hydroponic cultivation than under soil, thereby increasing total bacoside yield per plant. Reported effects on bacoside concentration were inconsistent, being higher in hydroponic tissue in some studies but higher in soil-grown plants in others; this divergence largely reflects differences in system design, nutrient formulation and role of other biotic factors (such as light quality) along with germplasm. Different hydroponic systems have shown variation in plant growth and metabolite yield thereof. Study have reported that the bacoside A3 yield varied across nutrient light combinations, peaking under phosphorus and potassium rich media combined with multi-spectral LED lighting. Elicitation further improved output; salicylic acid enhanced terpenoids yield several-fold. On the contrary, copper nanoparticles increased saponins by up to 89%, while copper sulphate and methyl jasmonate elevated bacoside A yield by regulating metabolic pathways. Collectively, the evidence indicates that optimised hydroponic cultivation can mimic or enhance soil-based bacoside production while offering faster, contaminant-free growth cycles.

Keywords: *Bacopa monnieri*, Brahmi, hydroponics, bacosides, elicitation, cultivation strategies.

INTRODUCTION

Bacopa monnieri contains a diverse array of bioactive constituents bacosides A and B, bacopa saponins, alkaloids, flavonoids and sterols of which the triterpenoid saponin bacosides are the principal pharmacologically active compounds [1]. Expanding commercial use of Brahmi in supplements, drugs and functional foods, together with growing pressure on wild populations, has created a clear need for cultivation strategies that reliably enhance both biomass and secondary-metabolite yield [2]. The species occurs throughout tropical and subtropical regions and grows best in

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warm, humid conditions (25–35°C, 60–80% relative humidity, slightly acidic to neutral soil pH and ample moisture), ecological factors that strongly influence biomass production and bacoside synthesis. This review compares the main cultivation approaches and identifies the conditions that maximize bacoside accumulation [3].

CULTIVATION STRATEGIES

Conventional field cultivation, usually by stem cuttings on loamy or sandy-loam soils with organic manures and NPK nutrition, is simple and economical but sensitive to climatic fluctuation and gives variable phytochemical content. In vitro micropropagation offers rapid clonal, disease-free and genetically uniform propagation independent of season; shoot and root development are governed by the balance of plant growth regulators, with cytokinins (e.g. BAP, kinetin) favouring shoot proliferation and auxins (IAA, IBA, NAA) favoring rooting [4]. Its principal drawbacks are high cost, contamination risk, potential somaclonal variation and acclimatisation losses. Hydroponic (soilless) culture supplies a balanced nutrient solution directly to the roots, enabling faster, space- and water-efficient growth, and has become the focus of efforts to raise bacoside yield in *B. monnieri*.

SYSTEMATIC ANALYSIS: METHODOLOGY & APPROACH

A structured semantic search of the published literature (>138 million records via the Elicit engine, which incorporates Semantic Scholar and OpenAlex) was performed using the query “hydroponic cultivation of *Bacopa monnieri* and the improvement in bioactive phytochemicals.” Of 1,000 retrieved records, most were excluded at abstract screening against predefined criteria (presence of a hydroponic component, quantitative phytochemical measurement, comparative design and peer-reviewed status), leaving 14 primary experimental studies for structured data extraction on system configuration, cultivation parameters, bioactive-compound results and growth metrics. The schematic work flow is shown Figure 1.

RESULTS AND DISCUSSION

Characteristics of Included Studies

The 14 studies spanned conventional hydroponic systems (NFT, DFT), container and static setups, bioreactor cultures and in vitro liquid systems, with durations ranging from 10 days to multi-year subculture (Table 1). Full texts were available for eight studies; the remainder were assessed from abstracts. Hoagland solution, at full or half strength, was the most commonly used nutrient base.

Biomass and Bacoside Content: Hydroponic Versus Soil

Hydroponic systems consistently increased biomass. The DFT system produced 8.48 g dry weight per plant, a 10.1-fold gain over soil [2], and NFT culture likewise raised fresh weight, shoot number and leaf number well above soil controls [3]. A key finding is that bacoside concentration (per unit weight) and total yield per plant do not always change in the same direction (Table 2). Under DFT, bacoside A3, bacopaside II and bacoside X concentrations were higher in soil, yet the far greater hydroponic biomass gave significantly higher total bacoside per plant ($p < 0.01$) [2]; bacopasaponin C, conversely, was higher in hydroponic tissue (1.45 vs. 0.81% DW) [2]. Kaur et al. and Datta et al. found bacoside concentrations 7.5% and roughly two-fold higher, respectively, in hydroponic plants [3, 4], whereas Inthima and Supaibulwatana reported 1.7- to 3.3-fold higher concentrations in soil—large enough to give soil-grown diploids the highest yield per plant [5].

System type, nutrients and light

Among configurations, DFT outperformed NFT for vegetative growth [2]. Bioreactors enhanced output markedly: balloon-type bubble and air-lift systems produced ~2.78- and ~1.75-fold more bacoside, respectively, than agitated- or shake-flask controls [6, 7], and reducing immersion time improved yield in a temporary-immersion system [8]. Nutrient and light optimisation was decisive: bacoside A3 varied about ten-fold (351–3528 mg/kg) across formulations within a single NFT system, peaking with

phosphorus- and potassium-rich media under multi-spectral LED light, although the formulation maximising biomass did not maximise bacoside concentration [9]. Blue light promoted shoot differentiation but did not significantly alter saponin yield between hydroponic and MS media [10].

Elicitation

Elicitors reliably enhanced secondary-metabolite production, with both dose and timing critical (Table 3). Salicylic acid raised terpenoids 5–7-fold [11]; copper sulphate elevated bacoside-A at 1–2 days post-treatment alongside upregulation of biosynthetic genes [12]; methyl jasmonate maximised bacoside A at 48 h with sequential gene upregulation [13]; copper nanoparticles increased saponins by up to 89% in a hormetic, dose-dependent manner [14]; and fungal elicitors raised bacoside-A up to 3.2-fold in tissue culture [15].

Table 1 Characteristics of the included studies

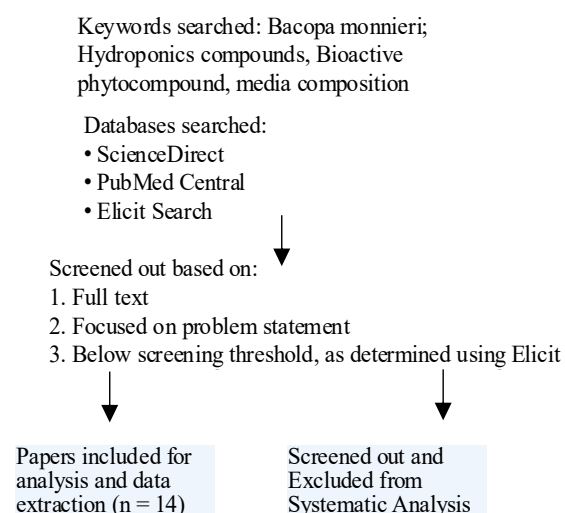
	Cultivation system	Key experimental factors	Duration	Bioactive compounds
Inthima & Supaibulwatana, 2024 [5]	Static hydroponic (hydroton), Hoagland	Hydroponic vs. soil; diploid (2x) vs. tetraploid (4x)	35 days	Bacoside A3, bacopaside II/X, bacopasaponin C, total bacosides
Maneeply et al., 2018 [2]	NFT and DFT systems	NFT vs. DFT vs. soil control	6 weeks	Bacoside A3, bacopaside II, bacoside X, bacopasaponin C
Vinay et al., 2025 [6]	Hydroponic (type unspecified)	Salicylic acid elicitation	6 weeks	Geniposidic acid, aucubin; broad metabolomics
Saste et al., 2025 [7]	NFT with cocopeat plugs	Four nutrient formulations; white vs. multi-spectral LED	7 weeks	Bacoside A3
Sharma et al., 2019 [8]	Glass-bottle (GBB) and balloon-type bubble (BTBB) bioreactor	Bioreactor type comparison	4 weeks	Total bacosides
Kaur et al., 2022 [3]	NFT with half-strength Hoagland	Five nutrient treatments; two cultivars	Kharif 2019–20	Bacoside-A
Lala, 2020 [9]	Static hydroponics, Hoagland	Copper nanoparticle (0–100 mg/L)	10 days	Saponins, alkaloids, phenolics, flavonoids
Aggarwal & Mathur, 2020 [10]	Hydroponic media “Leafy 200”	Hydroponic vs. MS media; blue vs. white light	Not stated	Saponins
Khiaokhoen et al., 2025 [11]	DFT with half-strength Hoagland	CuSO ₄ foliar (0, 250, 500 µM); multiple harvests	1–6 weeks	Bacoside A3, bacopaside II/X, bacopasaponin C, total bacoside A
Sujipuli et al., 2026 [12]	Hydroponic (type unspecified)	Methyl jasmonate (250 µM) foliar spray	3–48 h	Bacoside A
Kunakhonnuruk et al., 2023 [13]	Temporary immersion system (TIS)	System type; immersion time; explant density	Not stated	Bacoside A, bacopaside II, bacopasaponin C, total bacosides
Sharma et al., 2015 [14]	Shake flask, Growtek, air-lift bioreactor	Bioreactor type comparison	4 weeks	Bacoside A3, bacoside A2
Datta et al., 2024 [15]	Container hydroponics, custom nutrients	Hydroponic vs. soil comparison	3 weeks	Bacoside A, total bacosides
Parale & Nikam, 2009 [16]	Liquid/semi-solid MS media (tissue culture)	Auxins, cytokinins, fungal elicitors	≥2 years subculture	Bacoside-A

Table 2 Bacoside concentration versus total yield per plant, hydroponic vs. soil.

Study	Compound(s)	Concentration (per unit DW)	Total yield (per plant)	Direction
Inthima & Supaibulwatana, 2024 [5]	Total bacosides	Soil 1.5-fold higher (4x)	Soil 3.09/2.56 vs. hydro 2.22/1.95 mg/plant (2x/4x)	Soil higher (both)
Inthima & Supaibulwatana, 2024 [5]	Bacoside A3, bacoside X	1.7–3.3-fold higher in soil	Soil higher	Soil higher
Maneeply et al., 2018 [2]	Bacoside A3, bacoside II, bacoside X	Higher in soil	Significantly higher in hydro ($p < 0.01$)	Conc. soil; yield hydro
Maneeply et al., 2018 [2]	Bacopasaponin C	1.45% (hydro) vs. 0.81% DW (soil)	Higher in hydro	Hydro higher (both)
Kaur et al., 2022 [3]	Bacoside-A	7.5% higher in hydro	Not separately reported	Hydro higher
Datta et al., 2024 [15]	Bacoside A (extract)	19.93% (hydro) vs. 9.87% (soil)	Not separately reported	Hydro higher
Datta et al., 2024 [15]	Total bacosides (raw)	1.78% (hydro) vs. 0.74% (soil)	Not separately reported	Hydro higher

Table 3 Effects of elicitor treatments on bioactive-compound production.

Elicitor	Study	System	Key finding	Fold change
Salicylic acid	Vinay et al., 2025 [6]	Hydroponic	5–7-fold rise in geniposidic acid and aucubin vs. control	5–7-fold
CuSO ₄ (250–500 µM)	Khiaokhoen et al., 2025 [11]	DFT hydroponic	Bacoside-A rise at 1–2 days; biosynthetic genes upregulated	Total bacoside A 2.99–4.85 mg/g DW
Methyl jasmonate (250 µM)	Sujipuli et al., 2026 [12]	Hydroponic	Peak bacoside A at 48 h; sequential gene upregulation	Significant increase
Copper nanoparticles (0–100 mg/L)	Lala, 2020 [9]	Static hydroponics	89% rise in saponins; 204% in alkaloids; 116% in phenolics	Up to 3-fold (alkaloids)
Fungal elicitors	Parale & Nikam, 2009 [16].	Liquid MS medium	3.2-fold rise in bacoside-A in callus; 1.7-fold in shoots	1.7–3.2-fold

**Figure 1.** Workflow showing schematic workflow followed for systematic analysis.

CONCLUSION

Optimised hydroponic cultivation reliably increases the biomass and total bacoside yield of *B. monnieri*, and can match or exceed soil cultivation for bacoside concentration when nutrient formulation, light spectrum and elicitor treatment are tailored. The apparent disagreement between studies is largely

resolved by distinguishing concentration from total yield per plant, by the specific bacoside constituent measured, and by differences in system configuration and study quality. The most promising configuration combines a DFT system, multi-spectral LED lighting and phosphorus- and potassium-rich nutrient solutions with timed elicitor application (copper sulphate, methyl jasmonate or salicylic acid), offering a faster, controlled and contaminant-free route to sustainable bacoside production.

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