

Biochar as a Soil Amendment in Tropical Acidic Soils: Effects on Nutrient Retention and Crop Yield

Philippa Polglase¹ ●, Ebba Holmgren² ●, Mariana Figueiredo³ ●

¹ Associate Professor, Department of Soil Science and Agricultural Chemistry, Wensleydale Institute of Livestock Science, Leyburn, United Kingdom. Email: p.polglase@wils.ac.uk | ORCID: 0000-0001-2742-600X

² Research Associate, Department of Agronomy, Skane Centre for Crop Protection, Kristianstad, Sweden. Email: e.holmgren@sccp.se | ORCID: 0000-0001-0385-5248

³ Senior Research Fellow, Department of Agronomy, Alentejo Institute of Agrarian Sciences, Beja, Portugal. Email: m.figueiredo@aias.pt | ORCID: 0000-0001-3047-431X

ABSTRACT

Biochar, the charred residue of biomass heated with little oxygen, is often proposed as a way to repair acidic, weathered tropical soils: it may raise pH, bind aluminium, hold nutrients that would otherwise leach and, in the end, lift crop yield. This narrative review asks how far the published evidence supports that chain of claims, and where it breaks. It draws on work on soil acidity, on how feedstock and pyrolysis temperature shape biochar, on mechanisms of nutrient retention, on field and pot experiments in the tropics, and on ageing, economics and life-cycle assessment, and it reports no new data. The main complication is variability. Effects depend on feedstock, pyrolysis temperature, soil and application rate, and yield responses reported in the literature range from clearly positive to neutral to negative. Much of the benefit seen in acidic soils looks like a liming and nutrient-supply effect that fades or changes as the material ages, nutrient retention measured in columns is not always matched by better yield, and cost, ageing and field-scale evidence remain thin. The review concludes that biochar is a plausible but conditional amendment, suggests how trials should be reported and compared with lime and fertiliser, and lists the evidence needed before broad recommendations can be made.

Keywords: Biochar; Acidic soils; Tropical agriculture; Nutrient retention; Crop yield; Pyrolysis; Narrative review

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1. Introduction

Large areas of the humid tropics are covered by soils that are acidic, deeply weathered and poor in the nutrients crops need [1, 2]. Aluminium in solution damages roots [3, 4], calcium and magnesium are scarce, phosphorus is held tightly by iron and aluminium oxides, and heavy rain carries nitrogen, potassium and bases below the root zone [2]. For smallholders, the usual remedies of lime and mineral fertiliser are costly, hard to transport and not always available at planting time.

Biochar has therefore attracted a great deal of interest. It is the carbon-rich solid left when biomass is heated with little or no oxygen, and its appeal in the tropics rests partly on the dark, fertile anthropogenic soils of the Amazon, which contain large amounts of charred material [5, 6]. The expectation is that a charred residue can raise pH, bind aluminium, hold nutrients against leaching and in the end improve yield, while also storing carbon [7, 8, 9].

The difficulty is that each link in that chain is conditional. Quantitative summaries of the literature report an average benefit for crops that

is modest and varies a great deal between studies, with the largest responses in acidic and nutrient-poor soils [10, 11, 12]. Effects depend on the feedstock that was charred, the temperature at which it was heated, the soil it meets and the rate at which it is applied [13, 14]. Yield responses range from positive to neutral to negative, the material changes as it ages, the cost of producing and spreading it is rarely counted, and evidence at the scale of real farms is scarce. The aim is to separate what has been measured from what has simply been repeated.

This article is a narrative review. It sets out what is known about biochar in tropical acidic soils, with particular attention to nutrient retention and yield, and it is deliberately candid about the places where the evidence thins. It reports no new data, and where a number could not be checked against its source we have left it out.

2. Literature Review

2.1 Acidity, Aluminium and Nutrient Loss

Acid soils occupy a large share of the world's land and are concentrated in the humid tropics, where they limit production for many of the people least able to buy amendments [1]. The problems that come with low pH are several at once: toxic forms of aluminium, shortage of calcium and magnesium, and strong fixation of phosphorus. Plants differ in how well they cope, partly through the release of organic acids that bind aluminium outside the root [3, 4]. A crop on such a soil is rarely limited by one thing.

Soil classification systems built for the tropics make the same point from the other side. They describe how low-activity clays, low base saturation and coarse texture combine to give soils with little capacity to hold nutrients [2]. In such a soil, fertiliser nitrogen and potassium can be lost within weeks, and an amendment that improves retention would be useful even without any direct nutrient supply. This is the niche into which biochar is usually placed.

2.2 Feedstock and Temperature Shape the Product

Biochar is not one material. Characterisation studies show that feedstock and pyrolysis temperature together set its ash content, alkalinity, surface area, carbon structure and nutrient content [15, 16, 17]. Woody feedstocks give low-ash, stable chars; crop residues and manures give ash-rich chars with more nutrients and a higher pH; and industrial wastes such as paper-mill residues can give strongly alkaline

products [18]. Table 1 summarises these tendencies without attaching numbers to them, since values differ from batch to batch.

Temperature pushes in a consistent direction (Figure 1). Hotter pyrolysis tends to give a more alkaline, more aromatic and more stable product with less easily decomposed carbon, whereas cooler pyrolysis leaves more volatile matter and more oxygen-containing groups on the surface [16, 17]. The choice therefore trades one set of properties against another: the char most likely to act as a liming agent is not the one most likely to supply labile carbon or surface charge when fresh. Many papers report neither the temperature nor the feedstock in enough detail to say which was used, and that omission alone makes comparison difficult.

Table 1. Broad tendencies of biochar by feedstock class and pyrolysis temperature.

Feedstock class	Typical character	Main caution
Woody material	Low ash, stable carbon, modest nutrient content [16, 17]	Weak liming; little direct nutrient supply
Crop residues and husks	Moderate ash, potassium and silicon often present [15, 16]	Composition changes with crop and season
Manure and litter	Ash-rich, more nutrients and higher pH [15]	Salts; variable nitrogen availability
Industrial wastes (e.g. paper mill)	Alkaline, mineral-rich [18]	Contaminant screening needed [30]
Higher pyrolysis temperature	More alkaline, more aromatic, less labile carbon [16, 17]	Fewer surface oxygen groups when fresh
Lower pyrolysis temperature	More volatile matter and oxygen groups [15, 17]	Labile carbon may tie up nitrogen [21]

Note: Qualitative tendencies drawn from characterisation studies; individual biochars vary and no figures are given.

	Cooler pyrolysis	Hotter pyrolysis
pH, ash alkalinity	lower	higher
Aromatic carbon	less	more
Labile carbon	more	less
Surface O groups (fresh)	more	fewer
Pore development	less	more

Qualitative tendencies relative to each other; schematic, not data

Figure 1. How pyrolysis temperature tends to shift biochar properties (qualitative matrix, not data).

2.3 How Biochar Might Retain Nutrients

The best-known idea is that biochar adds cation exchange capacity. Black carbon in soils with a long history of charring shows higher exchange capacity, and the charge appears to arise as the surfaces oxidise over time [19, 20]. If true, fresh biochar would be a weaker exchanger than aged biochar, and the benefit for nutrient retention would grow after application instead of appearing at once. Ammonium is the nutrient most consistently reported as held back; nitrate is less certain [21, 22].

Column and incubation experiments often show less leaching from amended soil. In a temperate soil, biochar additions reduced the amounts of several nutrients that drained through columns [23], and in multi-layered columns biochar lowered ammonium loss [22]. A meta-analysis found reduced nitrate leaching on average, with the size of the effect depending on soil, biochar and land use [24]. Organic coatings that form on biochar surfaces, for example during co-composting or contact with soil organic matter, have been proposed as an important route for binding nutrients [25]. Table 2 lists the mechanisms discussed in this review together with the main reason for caution about each.

Table 2. Proposed mechanisms by which biochar may affect nutrient retention and yield in acidic tropical soils.

Mechanism	Plausible effect	Main caveat
Alkalinity of ash	Raises pH, eases aluminium stress [26, 28]	Equivalent to liming; fades with time
Surface charge	Greater cation exchange as surfaces oxidise [19, 20]	Slow for fresh biochar
Ammonium retention	Less ammonium leached [22, 24]	Weaker evidence for nitrate [21]
Organic coatings	Nutrient binding on aged surfaces [25]	Depends on contact with organic matter
Direct nutrient supply	Calcium, magnesium, potassium, phosphorus from ash [18, 27]	Depends on feedstock
Legume nitrogen fixation	More nitrogen fixed by common beans [29]	Few field confirmations
Nitrogen immobilisation	Possible loss of nitrogen to microbes [21]	Can cancel other gains

Note: Mechanisms are hypotheses supported to differing degrees; the last column states the main reason for caution.

2.4 Liming, Aluminium and Direct Nutrient Effects

In acidic tropical soils, a good part of the response to biochar may not come from retention at all. Ash

carries bases and carbonates, so biochar can raise pH and lower aluminium stress, and it also supplies calcium, magnesium, potassium and phosphorus in amounts that depend on the feedstock [18, 26]. In a Colombian oxisol, the yield benefit that emerged after the first year was linked to better calcium and magnesium nutrition [27]. A pooled analysis of tropical and temperate data likewise attributed higher tropical yields to the liming effect and the nutrients the material supplies [28].

Some responses seem to run through other channels. Common beans fixed more nitrogen after biochar additions, an effect tied to micronutrient availability and better nutrition rather than to pH alone [29]. The same literature also records harm. Biochar with a wide carbon-to-nitrogen balance can tie up soil nitrogen, at least for a time [21], and some materials bring salts or contaminants that matter for crops and for soil life [14, 30]. Positive, neutral and negative results can all be expected, depending on which of these processes dominates. Read this way, the headline figure of any single study matters less than the conditions behind it.

2.5 Ageing, Stability and the Tropical Setting

What is put on the soil is not what stays in it. Over months and years biochar surfaces oxidise, pick up organic matter and form associations with minerals, and its pores fill [31, 32]. Meta-analysis suggests that biochar carbon is decomposed slowly in soil, with some early effects on native organic matter that differ between studies [33]. Warm conditions speed oxidation and decomposition [34], which matters in the tropics because the properties that give a benefit may evolve faster there than in the cooler soils where much of the early work was done.

For this reason a trial that stops after one season cannot say what the second season will bring. Early gains from the liming effect of ash may fade as the alkalinity is used up, while surface charge and coatings that favour retention may develop later [20, 25]. Short studies capture only one phase of that sequence, and a result that looks like proof of a long-term benefit may be a transient. Soils that have had time to react with an amendment behave differently from soils sampled a few weeks after mixing.

3. Materials and Methods

3.1 Scope and Question

The review asks one question in two parts: does biochar applied to tropical acidic soils improve

nutrient retention, and does that translate into higher crop yield? We divided the question into the sub-questions that a study would need to answer: what biochar was used and how it was made, what soil it was added to, at what rate and with what fertiliser, over what time, and how cost was reckoned. Such differences look small in a table and loom large in a field.

3.2 Literature Assembly

The review draws on peer-reviewed reviews, meta-analyses and experimental papers in five areas: soil acidity in the tropics; characterisation of biochar by feedstock and temperature; mechanisms of nutrient retention; field and pot evidence from tropical and subtropical sites; and ageing, economics and life-cycle assessment. Studies from temperate soils are included only to illustrate mechanisms and are flagged as such. Sources were chosen for relevance, influence in the field and clarity of method.

We did not carry out a formal systematic search and we do not claim one. This is a narrative synthesis and the selection of sources reflects the authors' judgement. The practical consequence is that the review is a better guide to the structure of the evidence than to the exact size of any effect, and we avoid quoting effect sizes from individual studies that could not be checked against the primary papers for this article.

3.3 Appraisal Framework

To judge how far a report can be trusted for a given soil, we asked five questions of it. Were feedstock and pyrolysis temperature stated? Was the soil described well enough to tell whether it is truly acidic and base-poor? Were application rate and fertiliser regime reported, and was a fertiliser-only or lime control included? How long did the study run, and was it done in pots or in the field? And was the cost of obtaining and applying the biochar counted? Studies that answered most of these were given more weight in the narrative.

4. Results

4.1 What the Summaries Agree On

Pooled analyses agree on a general pattern: on average, crop productivity rises after biochar is applied, the rise is modest, and the spread between studies is wide [10, 11, 12]. The point is not that a study is weak, only that its result travels less far than its abstract suggests. Responses tend to be larger in acidic, coarse-textured and nutrient-poor soils, and they depend on experimental conditions such as pot versus field and fertiliser use [12, 13]. A comparison between

climatic zones found a benefit in tropical soils that was not seen in temperate ones [28]. Reviews of soil fertility effects reach a similar view that benefits are real but conditional [35].

4.2 Evidence from Tropical Acidic Soils

Several experiments in the tropics support the optimistic reading. On a highly weathered Amazonian upland soil, charcoal combined with mineral fertiliser gave better crop production than fertiliser alone and the benefit carried across seasons [36]. In the same soil type, charcoal with compost improved nitrogen retention and uptake [37]. Earlier comparison of an archaeological dark earth with an adjacent Ferralsol had shown how differently nutrients are held in the two soils [6]. In Indonesia, charred acacia bark was associated with higher soil pH, lower exchangeable aluminium and better nutrient status [26].

Other results are more mixed. In the Colombian oxisol, the yield effect appeared only after the first year [27]. Trials at five conservation-farming sites in Zambia reported effects that were not the same everywhere, which is what one would expect when soil, season and management all differ [38]. Waste-derived biochar on an acidic Australian soil improved some indicators of fertility, with crop responses that differed between species [18]. Table 3 gathers the conditions linked with each kind of outcome.

Table 3. Conditions associated with positive, neutral and negative yield responses to biochar.

Response	Conditions often reported	Sources
Positive	Acidic, base-poor soils; moderate rates; combined with fertiliser	[26, 28, 36]
Delayed positive	Yield gain appearing after the first season	[13, 27]
Neutral	Soils already adequate in nutrients and pH; short trials	[10, 12]
Mixed	Differs by crop, site and season on farms	[14, 38]
Negative	Nitrogen immobilisation; salts; excessive rates	[14, 21]

Note: Conditions are those discussed in the cited literature; none of the associations is universal.

4.3 Why Responses Run from Positive to Negative

No single factor explains the spread, but several recur. A biochar that is alkaline and ash-rich helps most where acidity or base shortage limits yield, and does little where it does not [26, 28]. A biochar with plenty of labile carbon can immobilise nitrogen when no fertiliser is added [21]. High

rates can bring salts or other unwanted effects, and the agronomic literature records both gains and losses depending on material and rate [14, 30]. Figure 2 shows how these questions can be turned into a path from soil and biochar to likely outcome; it is a way of thinking, not a model.

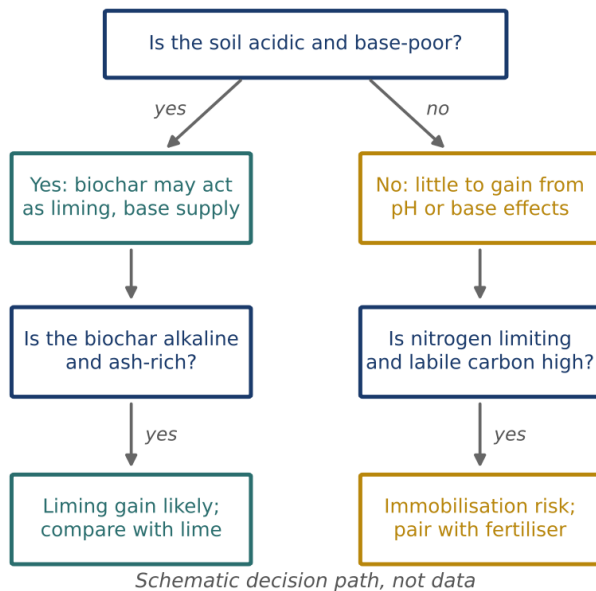


Figure 2. Questions that sort likely outcomes of biochar use on an acidic soil (schematic decision path, not data).

A further difficulty is that much of the apparent benefit looks like liming under another name. Few of the reports we drew on appear to have compared biochar with an equivalent liming treatment, so it is hard to say what biochar adds beyond neutralising acidity and supplying bases. If it adds little, then lime, where available, is the simpler and better-understood choice; if it adds retention and organic matter benefits, that case has to be shown with the right control. This is one reason the same material can look excellent in one report and unremarkable in the next.

4.4 Nutrient Retention: What Is Shown and What Is Assumed

Retention is easier to demonstrate than yield. Column and incubation studies give clean, repeatable results about leaching [22, 23], while field trials must deal with rainfall, root uptake and variability. The meta-analytic evidence for reduced nitrate loss depends on soil and biochar properties and on the setting [24]. Nitrogen held in the soil is also not necessarily nitrogen available to the crop, and immobilised nitrogen is a loss from the plant's point of view even if it is not leached [21].

The link from retention to yield is thus an inference rather than a measurement in many papers. Where retention improved and yield rose together, as with charcoal and compost in the

Amazon, the story is coherent [37]. Where yield rose with no clear change in retention, liming and direct supply may be the cause [26, 27]. Authors who measure both in the same plots are in the best position to say which mechanism matters, and few do. Absence of an effect in a small trial is not evidence that no effect exists.

4.5 Ageing, Cost and Field-Scale Gaps

Ageing makes interpretation harder (Figure 3). Fresh biochar, aged biochar and biochar mixed with compost behave differently, and conclusions from one cannot simply be applied to the others [25, 32]. Because warmth speeds oxidation [34], tropical trials of different lengths may be looking at different stages of the same process. A study of a few months and a study of several years are not testing the same thing, even when they use the same material.

Cost is the second gap. Life-cycle assessments find that the energy, economic and climate outcomes of biochar systems depend strongly on feedstock, on how the process is run and on what is assumed for the value of carbon and energy [39]. Economic analysis of biochar in crop production reached conclusions that depended heavily on the assumed yield benefit and price [40]. For a smallholder, the relevant sums include the labour of making or fetching the material, transporting it and incorporating it, and these are seldom reported. Without them, a statistically significant yield rise cannot be called profitable.

Properties that matter for acid soils change as biochar ages



Conceptual; time not to scale, not data

Figure 3. Conceptual timeline of biochar ageing in warm, wet soil (schematic, time not to scale).

The third gap is scale. Most of the controlled evidence comes from small plots, pots or columns, and the few on-farm trials show more variable results [38]. Long-term, multi-site experiments with realistic rates, a lime control and cost records are rare. Until they exist, the soundest reading of the tropical evidence is as a set of well-observed cases rather than a general rule. A benefit that

vanishes once the cost of the biochar is counted is not a benefit a smallholder would see. These points apply with equal force to any new amendment, not only to biochar.

5. Discussion

5.1 Interpretation

The central finding is conditional. In acidic, base-poor tropical soils, biochar often acts as a liming and nutrient-supplying amendment with an additional, slower contribution to retention as it ages [25, 28]. Where the soil is already adequate, or where the biochar is poorly matched to the soil, the response may be small or negative [10, 21]. The practical question is therefore not whether biochar works but which soil problem it would address and whether a cheaper tool would address it equally well. Nothing here argues against using biochar; it argues for measuring what it does on the soil in question.

The second conditional is economic. A material with a modest and uncertain yield effect needs to be cheap, local and easy to apply to pay for itself, and the biochar most likely to be affordable is not necessarily the one with the best properties [39, 40]. A household that already makes charcoal as a by-product may find that fines are a free input; a household that must buy feedstock and fuel may not.

5.2 Limitations

This is a narrative review and shares the limits of that form. The choice of sources reflects judgement, no formal search or quality scoring was done, and publication bias in favour of positive results cannot be excluded. We did not quote numerical effects from individual field trials because they could not be verified against the primary papers here. A reader who needs an effect size should consult the original studies and the meta-analyses cited, applying the appraisal questions above. Reviews are more useful when they say where the evidence stops than when they smooth it over.

The evidence base is also uneven. Much of it comes from a limited number of soils and regions, from pot experiments, or from temperate systems used to illustrate mechanisms [9, 23]. Conclusions about the humid tropics should be read with that imbalance in mind.

5.3 Implications for Practice

For advisers, the sensible position is neither to dismiss biochar nor to promise results. A household that wishes to try it can do so as a recorded pilot: treated and untreated strips on the

same soil, with a lime-only and a fertiliser-only strip if possible, the same crop and management, and yield and labour noted for each. Moderate rates, a well-characterised local feedstock and a full season or more of observation are preferable to a large one-off dose [27, 36].

5.4 Directions for Future Work

Four needs stand out. First, long-term, multi-site field trials in the tropics that include a lime control, a fertiliser control and several rates. Second, routine reporting of feedstock, temperature, ash, pH and exchange properties so that trials can be compared [15, 16]. Third, studies that follow ageing across seasons and link it to retention and yield [25, 32]. Fourth, full economic accounts that include labour and transport, ideally from on-farm trials [38, 40].

6. Conclusion

Biochar is a plausible and sometimes useful amendment for tropical acidic soils, but the claim that it improves nutrient retention and raises yield holds only under conditions that vary with feedstock, pyrolysis temperature, soil and rate. Much of the observed benefit can be explained by liming and nutrient supply, retention improves as the material ages, and yield responses range from positive to neutral to negative. Cost, ageing and field-scale evidence remain the weakest parts of the case.

For practitioners the message is practical. Match the biochar to the soil problem, test it against lime and fertiliser, record the costs and judge it over more than one season. For researchers, the opportunity lies in trials that are long, multi-site, properly controlled and fully costed, which would turn a promising idea into advice that smallholders can rely on.

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9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

P.P. conceived the review and wrote the sections on soil chemistry and nutrient retention. E.H. wrote the sections on field evidence and crop

responses. M.F. wrote the sections on ageing, economics and trial design. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No human participants or animals were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

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