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TOPICAL REVIEW

# Low-cost and labour-efficient innovations in household recycling of organic wastes for soil improvement

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**Keywords:** organic matter recycling, low-income households, soil improvement, composting, anaerobic digestion, pyrolysis, organic wastes

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## Abstract
Organic matter plays an important role in the health and productivity of soils, but its depletion is a common problem in households in low-income countries. This is due to lack of and competing uses for organic resources, and limited information on recycling methods. Therefore, here we review low-cost and labour-efficient innovations to improve recycling of organic wastes, stabilising residues so that soil organic matter can be increased with less inputs and enhancing nutrient content to produce a more effective organic fertiliser. Composting, anaerobic digestion and pyrolysis are all processes that stabilise organic matter. Innovations in treatments are needed to improve stabilization and control the release of nutrients so that they are available to crops in the right amounts and at the right time. This can be achieved by maintaining appropriate treatment conditions: for composting, carbon to nitrogen ratio 25–35, carbon to phosphorus ratio ~50, pH 5.5–8.5 and 50%–60% moisture content; for anaerobic digestion, carbon to nitrogen ratio 20–35, bulk density 0.6–0.8 g $cm^{-3}$, lignin

content < 7.5%, pH 6.8–7.4 and moisture content 85%–95%; and for pyrolysis, carbon to nitrogen > 40 and moisture content < 20%. Different methods to achieve these ideal conditions are discussed, including appropriate choice of treatment method, co-composting/co-digestion for ideal nutrient content, enhancing nutrients using collected urine, nitrogen-fixing plants, bioslurry or by inoculating with bacterial communities, absorbing excess nutrients on biochar, adjusting pH using wood ash or biochar, pre-treatment to break down lignin and cellulose, and designs to achieve ideal moisture and temperature. Innovations should also ensure that treatment processes do not overuse or compete with other important household resources, such as finances, water or labour. We draw together findings to identify methods with most potential to improve soils in low-income countries, providing decision tables to guide selection of approaches for different contexts.

## 1. Introduction

Organic matter plays an important role in the health and productivity of soils. It improves soil structure by binding sand and clay particles together into macroaggregates (Oades 1993, Rahman *et al* 2020). These large particles are less susceptible to erosion than the smaller disaggregated sand and clay particles (Macks *et al* 1996, Keller and Dexter 2012, Rahman *et al* 2022). They pack together to form soil pores, which allow water, air and roots to penetrate the soil (Thomas *et al* 1996, Sharma and Kumar 2023). Organic matter also increases water holding capacity through electrostatic interactions with water molecules (Murphy 2015, Lal 2020). It holds organic carbon (C) which facilitates microbial activity and slowly releases associated nutrients to plants when the organic matter decomposes (Kirkby *et al* 2011). Therefore, a soil with a high level of organic matter is more stable with reduced surface water runoff and improved infiltration compared to the same soil type but with less organic matter. It is less susceptible to erosion, allows deeper root penetration and provides more water and nutrients to plants. These are all factors that contribute to improved plant growth and crop production.

However, globally, Lal (2013) estimated that the organic C content of arable soils is depleted by 25%–75% compared to soil under natural land uses. Therefore, as well as increasing organic matter for crop production, recapturing atmospheric C in soils could significantly contribute to mitigation of climate change. The '4 per mille Soils for Food Security and Climate' initiative, recognized at the Climate COP21 in Paris, France in 2015, aspired to increase organic C in the top 40 cm of soil by 0.4% per year (4 per 1000). In a soil with a typical bulk density of 1.3 g $cm^{-3}$, this is equivalent to an increase in soil C of ~2 Mg $ha^{-1}$ per year. Lambin and Meyfroidt (2011) estimated that 11%–12% of the total global land area has potential to sequester C through improved crop management, and Lessmann *et al* (2022) estimated that improved crop management could sequester between 0.2 to 0.6 Mg $ha^{-1}$ per year, with the highest potential in regions characterised by low crop production, low initial soil organic C levels, and in regions where livestock manure and crop residues are only partially recycled. These areas typically correspond to low-income households in low-income countries. Therefore, methods for improved C sequestration in low-income households are of high global importance, as well as providing benefits to the household itself.

Organic matter is added to the soil by amendments of organic wastes, such as manure, debris from growing plants and inputs during microbial processes. It is lost from the soil by decomposition, erosion and runoff. Therefore, C can be sequestered by increasing inputs from organic wastes, plant production and microbial processes, or by decreasing losses by decomposition, erosion and runoff. Low inputs of organic matter to the soil represents, not only a missed opportunity for C sequestration and improved soil structure, but also a reduction in the circular economy of agriculture and a waste of scarce nutrient resources. In the highlands of Ethiopia, Negash *et al* (2017) observed that 85% ± 4% by dry mass of the biomass produced by households was used as fuel, representing a mean loss of 59 ± 2 kg $ha^{-1}$ per year nitrogen (N), 13.9 ± 0.3 kg $ha^{-1}$ per year phosphorus (P) and 79 ± 2 kg $ha^{-1}$ per year potassium (K). Therefore, in this review article, we focus on improved recycling of organic wastes in low-income households, examining innovations that increase organic inputs, stabilise organic matter and increase availability of nutrients, aiming to simultaneously increase C sequestration, soil organic matter content and crop production.

## 2. Why do we need innovations?

Recycling of organic waste is a well-known and traditional practice to improve soils in many places of the world, so why are new innovations needed? Innovations are needed because there are many competing uses for organic wastes that prevent recycling, and this is exacerbated by the rising global population with further limitations in low-income households (Negash *et al* 2017). Organic 'wastes' are actually valuable resources; globally, approximately 7%–16% are used for fuel (Smil 1999, Goldenberg 2003) and 24%–40% for animal feeds and bedding (Smeets *et al* 2007). In addition, crop residues and dung are widely used in building (Dadi *et al* 2020). In 2016, biomass made up 7.8% of global final energy consumption (REN21 2018). In a survey of households in south-west Bangladesh, Islam *et al* (2024) observed that 56% of farmers used most of their manure as fuel, while in Nepal, 54% of households were reported in 2023 to be dependent on traditional fuel (firewood, dung cakes and agricultural residues) for cooking (WECS 2023). High use of cow dung as fuel is also observed in the Terai region of Nepal (Krupnik *et al* 2021, Adhikari *et al* 2023). Therefore, if organic and nutrient inputs to the soil are to be increased, we need innovations that replace the other uses of organic wastes, or we need methods that produce residues that can be incorporated into the soil at the same time as meeting other needs. For energy provision, these residues include the bioslurry remaining from anaerobic digestion to produce biogas (Smith *et al* 2014a), the fermented residues from bioethanol production (Lynd *et al* 2024), and the biochar produced by pyrolysis cookstoves (Smith *et al* 2023). Batchelor *et al* (2018) assessed the potential for home-scale photovoltaics to replace cooking fuel in low-income countries. However, while these could replace purchased fuels, such as liquid petroleum gas or kerosene, they are too costly for households who use their own organic wastes as fuel.

If households are to continue to use biomass to provide energy, we need innovations that stabilise the reduced amount of organic matter that is available to be incorporated into the soil so that more of the C is retained. Smith *et al* (2014a) estimated that when untreated organic wastes are incorporated into the soil, up to ~20% of the C content can be retained over the long term. In comparison, for bioslurry this increases to ~75% (a similar value to fermented residues) (Lynd *et al* 2024), for compost this is ~80% and for biochar C retention can be as high as 96%. Accounting for the losses of C that occur during the treatment process, 30%–40% of the C in the original feedstock is likely to be sequestered by composting or pyrolysis, an increase of 10%–20% over untreated wastes (Smith *et al* 2014a). Similar levels of C sequestration are achieved by applying the same amount of bioslurry or fermented residues as untreated waste, but with the advantage that anaerobic digestion and fermentation also provide an energy source so would lead to more organic wastes being available for soil incorporation in households reliant on biomass for energy (Smith *et al* 2014a, Lynd *et al* 2024).

Innovations in treatments are also needed to control the release of nutrients so that they are available to crops in the right amounts and at the right time, as well as to enhance the nutrient content of the organic matter. For the N in soil organic matter to be released to plants, the organic matter should have a C:N ratio of 10 to 15 (Mahapatra *et al* 2022); if the C:N ratio is higher than 15, N will tend to be immobilised by microbes during decomposition, while if it is much lower than ~8, the release of N will be too rapid, and N will tend to be leached or volatilized from the soil instead of being taken up by plants.

Finally, if recycling of organic wastes is to be feasible, innovations are needed to ensure other important household resources, such as finances, water, energy and labour, are not overused (Orskov *et al* 2014). Expenditure on energy can be reduced by treatment processes being done on-farm, but in areas with high cropping intensity, innovations in off-farm recycling methods may be needed, as the short time window between crops can make it difficult to incorporate residues (Smith *et al* 2023). Furthermore, we need to ensure that the pathogen contents of recycled organic wastes are within safe limits for application to agricultural land. Therefore, this paper reviews low-cost, household-scale innovations in recycling of organic wastes that increase the amount and stability of organic matter incorporated, and the availability of nutrients to plants, while also minimising cost, and limiting water and labour requirements for the treatment process. To be feasible, these must use locally appropriate technologies, be socially acceptable and provide economic benefits to the household (Tolessa 2024). Innovations should also reduce unused organic waste, so improving the household environment by converting waste into a valuable product. This will increase the sustainability of agriculture, support food security and nurture a circular economy at the community level.

Here we consider three major treatment methods; composting, anaerobic digestion and pyrolysis. We examine adaptations to these methods to make them more suitable for use by low-income households. Fermentation is not considered as there has been limited use to date of bioethanol as a household fuel in low-income countries, but this is something that may become more important in the future. The method selected to recycle the available organic wastes depends on its origin, abundance and composition, and the other resources available to the household (figure 1). If the household does not need to use organic waste as a source of energy, composting is a good option as it is low-cost, improves the supply of nutrients and stabilizes the organic matter in the soil. If the available organic waste is low in nutrients or dry, innovations are needed to improve the nutrient content of the compost and increase the rate of composting, while avoiding increasing financial costs or requirements for water or labour. If the household uses the organic waste as an energy source, nutrient rich wastes should be used in anaerobic digestion to produce an alternative clean energy source, as biogas. However, innovations are needed to reduce or meet water requirements, especially for dry feedstocks, and to reduce financial costs, labour and nutrient losses from the bioslurry. Nutrient poor and dry wastes are better used to provide energy by pyrolysis; innovations are needed to enrich and so improve the quality of the biochar

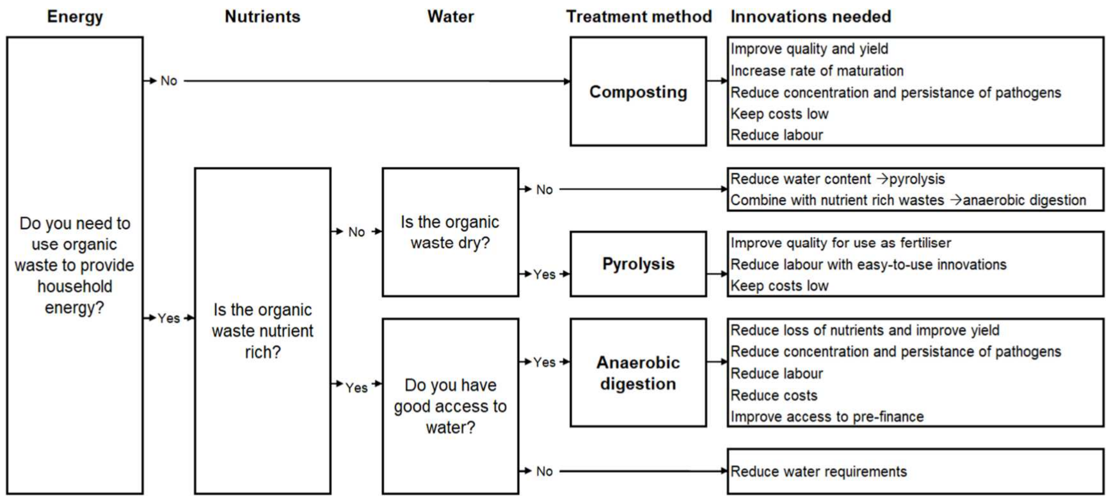


**Figure 1.** Decision tree for selecting methods and innovations for recycling organic wastes.

allowing it to be used as an organic fertiliser, and to reduce labour and financial costs. For nutrient poor wastes that are wet, innovations are needed, either to dry the waste before pyrolysis, or to increase the nutrient content so that it is suitable for anaerobic digestion. The innovations in composting, anaerobic digestion and pyrolysis that are suitable for use in low-income households are discussed in more detail in the following sections.

## 3. Innovations in composting

Composting is the process of aerobic decomposition of biodegradable solid organic waste into stabilized humic-like compounds. Interrelated changes occur during composting in temperature, pH, nutrient composition, mass, volume, free air space and moisture content. This is controlled by processes of microbial degradation, heat transfer and mass transfer (Walling *et al* 2020). Bacteria, fungi and actinomycetes decompose the organic matter leading to release of energy and water, which results in heating of the compost and a change in the decomposer communities (Walling *et al* 2020). The pH initially falls due to release of organic acids, but then slowly increases due to microbial consumption of the acids (Walling *et al* 2020). In order to avoid plant nutrient deficiencies or nutrient losses to the wider environment, a mature compost should neither lock up nor over-supply available nutrients to the soil. The process of composting uses the micro-organism demand for nutrients to homogenise the C to nutrient content of the organic waste. This produces a compost that provides a more consistent supply of nutrients than in the initial feedstocks. The aerobic decomposition process emits C as carbon dioxide ($CO_2$), so reducing the overall C to nutrient ratio and increasing the availability of nutrients. Similarly to soil organic matter, a high-quality compost has a C:N ratio of 10 to 15, which allows N to be slowly released to plants on application to the soil with minimum immobilisation of plant-available N (Mahapatra *et al* 2022). For P, the ideal C:P ratio is less than 50 (Chen *et al* 2022). Some P may be lost through leaching or movement of adsorbed P on organic particles, but the loss of C during composting usually increases the final concentration of plant-available P compared to the feedstock (Wei *et al* 2015). Being non-structural, K is quickly released and remains readily available in ionic form so there is high potential for loss (Nishanth and Biswas 2008, Irshad *et al* 2011, Maleki *et al* 2023). Nevertheless, the concentration of K in compost is usually higher than in the initial feedstock due to the release of C from the organic matter (Dimitrijević *et al* 2017). Micronutrients, such as iron, manganese and zinc, are often chelated by organic matter in compost, which improves their stability and moderates their availability for plant uptake (Hargreaves *et al* 2008).

Innovations in household composting focus on optimising the conditions controlling the decomposition; the C:nutrient ratio, pH, moisture and temperature. This aims to provide a rapid process that will maximise throughput and quality of the composted product. A range of different strategies can be used to achieve this, some of which are appropriate for low-cost applications (Awasthi *et al* 2022). In addition, innovations have been developed to enhance the nutrient content of the compost so that its value as a fertiliser is increased (Saha *et al* 2020). Further innovations aim to reduce requirements for labour and finances, to reduce the time of composting and to address problems associated with pathogens, odours, flies and leachates (Sharma *et al* 2023). Key innovations to achieve ideal conditions for efficient composting are depicted in figure 2.

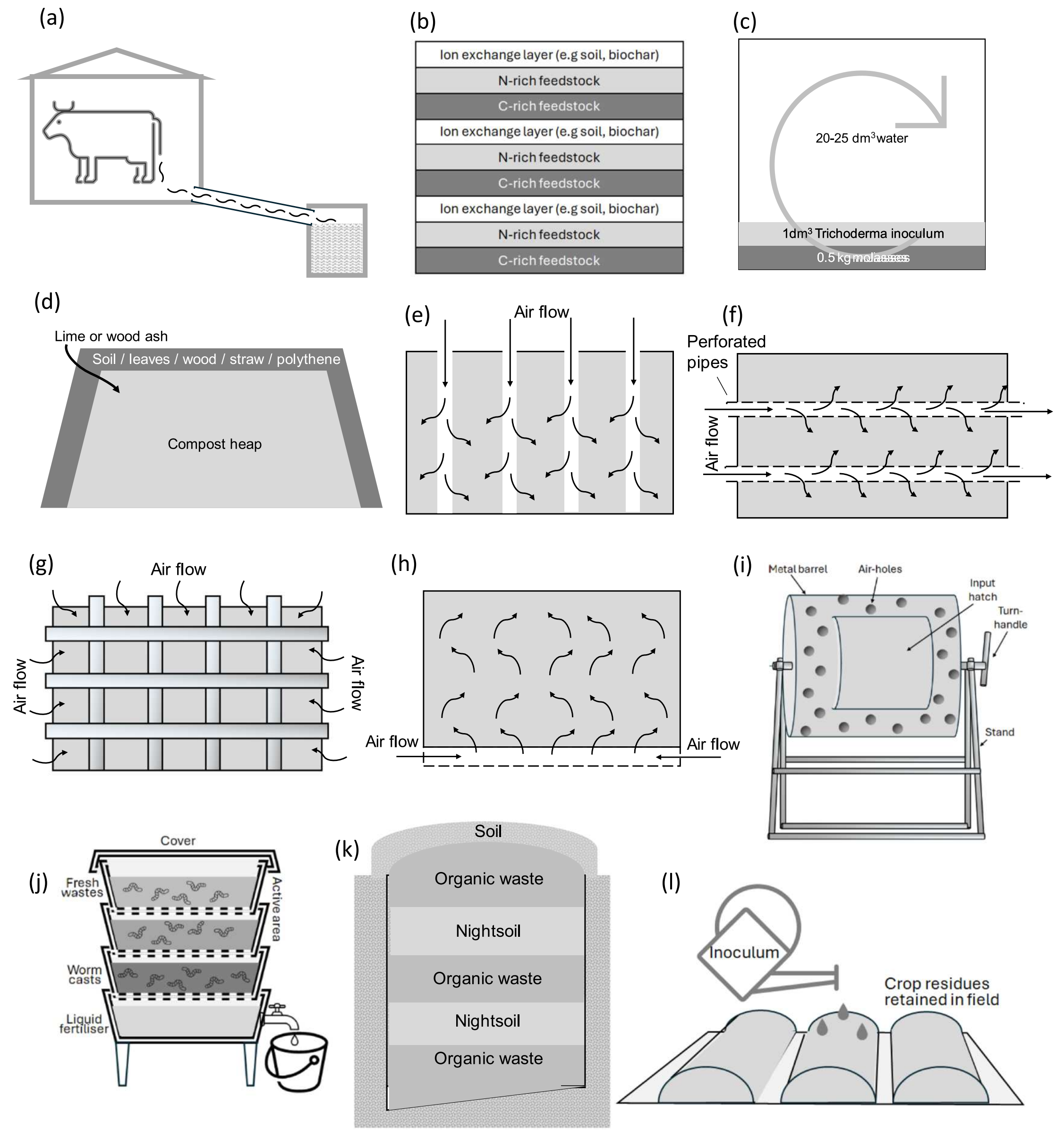


**Figure 2.** Schematic of low cost and labour efficient methods for improving compost; (a) collection of urine from housing to add nitrogen to compost, (b) layered co-composting to achieve optimum C:N, C:P, pH and water content, (c) culturing Trichoderma inoculum on-farm to add to compost, (d) addition of lime or wood-ash and use of low-cost compost covers to avoid losses of nutrients and acidification, (e) bamboo poles inserted and then removed to create air channels, (f) open-ended perforated pipes to allow air-flow, (g) bamboo or brick structure to allow air percolation from sides, (h) building compost on lattice of branches or platform to allow aeration from below, (i) rotary drum composter to allow daily turning with reduced labour, (j) use of insects to increase aeration—worms or black soldier fly larvae, (k) pit composting to increase insulation (nightsoil is collected human excreta), (l) in-field composting to reduced labour.

### 3.1. Carbon to nutrient ratio

According to Kumar *et al* (2010), the optimum C:N ratio in the feedstock for a rapid and effective composting process is 30 to 35. This is higher than in the soil or mature compost (10 to 15) due to the lack of homogeneity in the feedstock. A C:N ratio above 35 limits the rate of decomposition due to a lack of N for protein synthesis and growth, while a C:N ratio below 30 may result in losses of available N by volatilisation ($NH_4^+ + OH^- = NH_3 + H_2O$). Misra *et al* (2003) recommends a lower C:N ratio of 25 to 30. This lower recommendation may be because the optimum range for the C:N ratio is affected by the chemical composition of the feedstock. The complex chemical structure of lignin can make it more recalcitrant to decomposition (Richard 1996) and insoluble condensed tannins can bind cell walls and proteins, making them less physically and chemically available for decomposition (Schorth 2003). Therefore, the C:N ratio of the material that is accessible to the micro-organisms in organic wastes containing a large amount of lignin or tannins may be lower than apparent from the total chemical analysis.

Table 1 shows the typical composition of materials used for co-composting. Chen *et al* (2022) observed that a C:P ratio of 50 enhanced the rate of organic C degradation and accumulation of available P in kitchen wastes

**Table 1.** Typical compositions of example materials used for co-composting.

| Feed-stock | Dry matter content (g per 100 g wet feedstock) | C:N ratio | C:P ratio | K content (g per 100 g dry matter) | Bulk density (g cm$^{-3}$) | pH | Lignin content (g per 100 g dry matter) | Cellulose content (g per 100 g dry matter) |
|---|---|---|---|---|---|---|---|---|
| Poultry manure | **23–42**<br>25, 42, 37, 25–38, 23[a,b,c,e,f] | **3–10**<br>3.8, 8.3, 6.1, 3–10, 7, 3.8[b,c,d,e,f,g] | **19–21**<br>21.2, 18.9[d,f] | **3.8–6.1**<br>3.79, 6.1[d,f] | **0.81–0.96**<br>0.81–0.96[e] | **6.1–6.6**<br>6.63, 6.1[b,g] | **1.7–8.4**<br>1.7, 6.1, 1.7–8.4[b,d,h] | **4–44**<br>4.00, 4.4–44.0[b,h] |
| Pig manure | **9–48**<br>9, 48, 9–35[a,b,e] | **9–19**<br>10.0, 9.8, 9–19[b,e] | **25**<br>25.1[d] | **2.2**<br>2.16[d] | **0.32**<br>0.324[i] | **7.3**<br>7.29[b] | **1.8–18.4**<br>1.83, 7.9, 1.8–18.4[b,d,h] | **15.9**<br>15.86, 11.9–32.4[b,h] |
| Cattle manure | **10–33**<br>10–15, 19, 13–33[a,b,e] | **11–30**<br>15.9, 14.2, 11–30[b,d,e] | **32**<br>32.3[d] | **2.1**<br>2.11[d] | **0.78–0.99**<br>0.78–0.99[e] | **8.2**<br>8.27[b] | **8.0–18.2**<br>7.95, 14.6, 8.0–18.2[b,d,h] | **17.9–23.5**<br>23.51, 17.9–23.5[b,h] |
| Horse manure | **20–41**<br>20, 21–41, 23[a,e,j] | **22–50**<br>22–50, 27.5[e,j] | **96**<br>95.5[j] | **1.1**<br>1.08[j] | **0.72–0.96**<br>0.72–0.96[e] | **6.9**<br>6.87[j] | **2.2**<br>2.23[k] | **28.8**<br>28.8[k] |
| Food waste | **4–96**<br>4–95.5[l] | **6–64**<br>5.8–63.6[l] | **0–1**<br>0.01–0.25[l] | **0–9**<br>0.04–9.1[l] | **0.6–0.8**[m] | **3.8–6.9**[l]<br>3.8–6.9 | **0.1–20.4**<br>0.1–20.4[l] | **0.5–60.0**<br>0.5–60.0[l] |
| Rice straw | **88–93**<br>88–93, 92–93[e,p] | **59–113**<br>113, 59–78[e,n] | **289–923**<br>289–923[p] | | **0.11–0.19**<br>0.11–0.13, 0.16–0.19[e,o] | | **4–16**<br>13.8–16.1, 13.5, 4.3–7.0[n,p,q] | **43–46**<br>43.6–46.1[n] |
| Barley straw | **73–96**<br>73–96, 93, 86.5[e,s,t] | **48–150**<br>48–150[e] | | | **0.03–0.22**<br>0.03–0.22[e] | | **8–15**<br>14.8, 7.6–8.0[r,s] | **40**<br>38.8–40.2[s] |

Range of values found given in bold. Values from different sources given below. Where more than 1 number given, the sources are given in order of the list of numbers;

[a] FAO table 3.1. https://www.fao.org/fileadmin/user_upload/affris/docs/NewCommonCarp/carpT3–1.pdf;

[b] Li *et al* (2015)—manure from Fengxian county, of Shanghai city, China;

[c] Pop *et al* (2019)—chicken manure from Bucharest, Romania;

[d] Adekiya *et al* (2020)—Manures from Nigeria;

[e] Rynk *et al* (1992)—US organic wastes;

[f] de Vrije *et al* (2025)—Bonaire poultry manure;

[g] Singh *et al* (2018)—Chicken manure from Malaysia;

[h] Orlando and Borja (2020);

[i] Ackerman and Cicek (2013)—Pig manure from Canada;

[j] Chastain (2022)—Horse manure from US;

[k] Hadin and Eriksson (2016)—Horse manure from Sweden;

[l] Moonsamy *et al* (2024)—Lit. review of food waste;

[m] Favoino—https://www.compostnetwork.info/wordpress/wp-content/uploads/10_Favoino_Separate-collection_Italy_Seminar_Poznan.pdf Italian food waste—unpublished;

[n] Devêvre and Horwáth (2000);

[o] Zhang *et al* (2012)—rice residues across three continents;

[p] Kadam *et al* (2000) - Rice grown in a field trial in US;

[q] Rahman *et al* (2010)—Rice in Rajshahi, Bangladesh;

[r] Jin *et al* (2009)—Barley straw in China;

[s] Raud *et al* (2021)—Barley straw from Tartu, Estonia;

[t] Tumuluru *et al* (2014)—Barley straw from US

composted with rock phosphate and inoculated with phosphate-solubilizing bacteria. Higher C:P ratios resulted in accumulation of P in the microbial fraction (Chen *et al* 2022). When N is non-limiting, lower C:P ratios are likely to result in release of excess available P. Dao and Schwartz (2010) observed that there was no reduction in the rate of P mineralisation when available P was added to composts, suggesting that P mineralization occurs alongside the degradation of P-containing organic substrates and is incidental to the microbial P needs. Therefore, when N is not limiting, materials with low C:P ratios are likely to release excess P, which is then susceptible to loss to the wider environment. This is usually the case with animal manures (Dao and Schwartz 2010), so feedstocks should be blended to ensure the C:P ratio remains close to 50.

Co-composting of different feedstocks to maintain the ideal C:nutrient ratio can be achieved using look-up tables of the C and nutrient content of available feedstocks. This is usually centred around the C:N ratio as the N content most often limits decomposition. To counter N limitation, low C:N feedstocks should be added. If low C:N feedstocks are not available, bioslurry from anaerobic digestion usually has a low C:N ratio due to the removal of C as methane ($CH_4$) in the biogas (see later sections), and this can be mixed in to achieve the optimum C:N ratio. Other feedstocks that could be used to increase the N content of composts include N-fixing under-utilized plants that may be growing wild around the farm (Brito *et al* 2015), or urine that can be directed to a collection tank through channels in animal housing and used to further increase the N content of the compost (Nguyen and Nguyen 2018, ICIMOD 2020a), as seen in figure 2(a).

The amount of the second feedstock ($F_2$) that should be included, $M_{F2}$ (t), can be calculated by equation (1).

$$M_{F2} = \frac{p_{DM,F1} \times M_{F1} \times (r_{Co} - r_{F1})}{p_{DM,F2} \times (r_{F2} - r_{Co})} \tag{1}$$

where $M_{F1}$ is the amount of the main feedstock (Mg), $p_{DM,F1}$ and $p_{DM,F2}$ are the proportions of dry matter in the main and second feedstocks (g per g feedstock), and $r_{F1}$, $r_{F2}$ and $r_{Co}$ are the C:N ratios, respectively, of the main feedstock, the second feedstock and the target for the co-compost (mid-point 35–25 = 30). If the target C:N ratio cannot be reached with feedstocks 1 and 2, the C:N ratio following combination of the available amounts of feedstocks 1 and 2 can be calculated and then additional feedstocks included until the target ratio is achieved. This equation can similarly be used to determine the amount of feedstock needed to adjust the concentration of other nutrients in the compost by substituting in the appropriate C:nutrient ratios.

Co-composted materials are usually layered within the compost, making it easier to estimate the required proportions, as seen in figure 2(b). For example, Misra *et al* (2003) describe how the Indian Coimbatore method uses 5 cm layers of low nutrient content straw, vegetable waste, leaves and weeds with 5 cm layers of animal dung. This is done in a 90 cm deep pit until the heap is 60 cm above ground level. The above ground heap is plastered with mud to reduce nutrient losses. It is then left to slowly decompose for ~4 weeks until it flattens, when the mud is removed and the heap is turned. Turning the compost mixes up the layers to homogenise the nutrient contents of the different materials. Variations on the layering approach are used in the Indian Indore pit, Indian Indore heap, Chinese pit, Chinese high temperature, Ecuador heap and North Dakota State University hot composting methods, but with more prescriptive approaches for dealing with recalcitrant material and more turning to speed-up composting (Misra *et al* 2003). Modifications to the layers can be used to account for the different compositions of feedstocks available. To do this, equation (1) can be translated into the ratio of the depth of layers required using the bulk density of the main and second feedstocks, $D_{F1}$ and $D_{F2}$ (g $cm^{-3}$), respectively, according to equation (2).

$$V_{F2}/V_{F1} = \frac{M_{F2} \times D_{F1}}{M_{F1} \times D_{F2}} \tag{2}$$

where $V_{F1}$ and $V_{F2}$ are the volumes of feedstocks 1 and 2, respectively; if the width and length of the compost heap are approximately constant between layers, this ratio is also the ratio of the depth of layers of feedstocks 1 and 2. Similar calculations can be done for P if it is considered to be limiting rather than N.

The values required to calculate the depths of layers are given in table 1. For example, if the main feedstock on a farm is poultry manure ($p_{DM,F1}$ = mid-range 25–42 = 34, $r_{F1}$= mid-range 3–10 = 7), and the feedstock available for co-composting is rice straw ($p_{DM,F2}$ = mid-range 88–93 = 91, $r_{F2}$= mid-range 59–113 = 86), the amount of rice straw required to co-compost with each 1 Mg of poultry manure is $34 \times (30 - 7)/91 \times (86 - 30) = 0.16$ Mg. If the bulk density of the poultry manure, $D_{F1}$, is mid-range 0.81–0.96 g $cm^{-3}$ = 0.89 g $cm^{-1}$ and of the rice straw, $D_{F2}$, is mid-range 0.11–0.13 g $cm^{-3}$ = 0.12 g $cm^{-1}$, then the depths of the rice straw layers should be $0.16 \times 0.89/0.12 = 1.2$ times that of the poultry manure layers (approximately equal depths of rice straw and poultry manure).

The nutrient content of the compost produced can be increased to improve its' value as a fertiliser by adding materials with a high ion exchange capacity. These have potential to absorb nutrient ions and so reduce their losses during composting, producing a higher quality compost that efficiently delivers more nutrients to the crop with reduced losses to the wider environment. This has been done by adding clay minerals (or soil), coir dust or zeolites (Saha *et al* 2020), biochar (Smith *et al* 2023) or carbonate (Wang *et al* 2022), as seen in figure 2(b). Adding biochar (see later section) also increases long-term C sequestration, helps to maintain the moisture content and reduces greenhouse gas emissions during composting (Bello *et al* 2023, Liu *et al* 2023). Bokashi composting is a method that uses this approach by layering dry organic waste and manure with soil, biochar and bran, sprinkled with molasses, yeast and water with frequent turning to speed up decomposition (Kalala 2023). This produces a mature compost with highly available nutrients and soil improving properties in only 12–15 days (Quiroz and Céspedes 2019, Kalala 2023).

If after co-composting the C:N ratio remains too low, ammonia-oxidising bacteria can be added to the compost to reduce the losses of N by volatilisation (Zhang *et al* 2016). Inoculation with these bacteria (*Bacillaceae*) has been demonstrated to also improve the formation of humic substances and to stabilise the organic compounds in the compost (Xu *et al* 2022). Composts can also be enriched with nutrients or nutrient-transforming micro-organisms to further improve their value as fertilizers (Epstein 1997, Sanchez *et al* 2017). Some micro-organisms used to bio-fortify composts have also been observed to suppress soil borne pathogens and help to control plant diseases (Pugliese *et al* 2011, Harman *et al* 2004). A range of N-fixing bacteria have been isolated and used to increase the N content of compost, including *Achromobacter*, *Alcaligenes*, *Caulobacter*, *Klebsiella*, *Pseudomonas*, *Stenotrophomonas* and *Xanthomonas* (Pepe *et al* 2013).

For P, animal manures usually contain high amounts of phosphate, but in composts produced from plant materials only, the concentration of phosphate may be insufficient to meet crop requirements. Phosphate levels can be increased by mixing in rock phosphate (Odongo *et al* 2007) or human excreta (although care should be taken with sanitation; Jean-Baptiste and Monette 2024). The availability of the immobile P held in the compost can be increased by treating the compost with P-solubilizing bacteria, such as *Aspergillus, Bacillus, Arthrobacter* (Khan *et al* 2007, Chen *et al* 2022). For example, co-composting of biodegradable kitchen waste along with rock phosphate, biochar and plant growth promoting bacteria was observed in rice cultivation to reduce use of urea by 30% and of triple super phosphate fertilizer by 100% (Naher *et al* 2018). Similarly, for K, availability can be increased by inoculating the compost with K-mobilizing bacteria, such as *Aspergillus Awamori* (Nishanth and Biswas 2008).

If such inoculums can be cultured on-farm or supplied in a low-cost form, then inoculation with micro-organisms could be a feasible and important approach to enrich the nutrient content of composts in low-income households (Greff *et al* 2022). The Indian Indore method inoculates the compost with inoculum taken from the bottom of a mature compost pit (Misra *et al* 2003). Low-income farmers can reduce costs by purchasing inoculum from a commercial source and then multiplying it on-farm using molasses to boost the micro-organisms (Misra *et al* 2003). Trichoderma are naturally occurring fungi that have been included in commercial inoculums to speed-up composting by increasing enzymic activity (Matin *et al* 2019). The inoculum is easy to mass produce and enhances nutrient release by breaking down the organic matter more rapidly (Harman *et al* 2004). It also has the added benefit of disease suppression and is widely used as a biological agent to control soil-borne plant pathogenic microorganisms and plant diseases (Timila and Manandhar 2020, Shetty *et al* 2025). Rahman and Birkey (2015) described its use by mixing 1 $dm^3$ of Trichoderma inoculum with 0.5 kg of molasses and 20–25 $dm^3$ of water per ton of compost, as seen in figure 2(c). Further work is needed to fully characterise the efficacy of different inoculums in different working farm conditions, as well as examining their robustness to transport and storage.

### 3.2. Acidity

The optimum pH for aerobic decomposition is between 5.5 and 8.5 (Meena *et al* 2021). Fungi dominate decomposition under more acidic conditions (Yuvaraj and Ramasamy 2020). They can be effective at breaking down recalcitrant compounds, such as lignin and cellulose, but the rate of decomposition is much slower than bacterial decomposition (Ullah *et al* 2023). Therefore, an acidic compost can fail to achieve the temperatures needed to facilitate decomposition and kill weed seeds and pathogens (FAO 2003). Unfortunately, as shown in table 1, many organic wastes tend to be acidic (e.g. the pH of food wastes typically ranges between 3.9 and 6.9). If the compost heap fails to heat up despite optimum conditions for nutrients and moisture (see next section), the compost may have become acidic, requiring further action to return the pH to the optimum range.

Again, co-composting can be used to help maintain the pH within the optimum range. The pH of the co-compost can be approximately calculated by equation (3).

$$pH_{Co} = \frac{(M_{F1} \times pH_{F1}) + (M_{F2} \times pH_{F2})}{M_{F1} + M_{F2}} \tag{3}$$

where $pH_{F1}$, $pH_{F2}$ and $pH_{Co}$ are the pH of the main feedstock, feedstock 2 and the co-compost respectively (table 1). Note that accurate calculation of the change in pH would require the buffering capacity of the added feedstocks to be accounted for. However, in a low-income setting, this would be impractical. Therefore, this equation provides an approximation, which should hold over small pH ranges. In practice, the feedstocks are usually co-composted to achieve the optimum C:N ratio, with the proportions of the different feedstocks constrained to avoid the pH becoming too low or too high.

Rapid release of organic acids during the early phases of decomposition can further increase acidity. Using feedstocks within the optimum C:N range can help to avoid the compost becoming too acidic; both immobilisation of mobile N at high C:N ratios ($R\text{-}OH + NH_4^+ + OH^- = R\text{-}NH_2 + 2\,H_2O$) and volatilisation of ammonium ($NH_4^+$) at low C:N ratios ($NH_4^+ + OH^- = NH_3 + H_2O$) use hydroxyl ($OH^-$) ions and so increase acidity.

Lime or wood ash can be added to the compost to avoid the pH falling below the optimum range for decomposition (figure 2(d)). Lime or rock phosphate can also increase the rate of decomposition of high lignin materials by stimulating the microbial population and weakening the lignin structure (Misra *et al* 2003). However, volatilisation of $NH_4^+$ to ammonia ($NH_3$) is favoured under alkaline conditions (because the reaction requires $OH^-$), so if the compost contains high levels of $NH_4^+$, liming must be done with care to avoid increased losses of Wang *et al* (2016a) found that combining liming materials with struvite (magnesium ammonium phosphate, $NH_4MgPO_4{\cdot}6H_2O$, which can be extracted from wastewater) can help to maintain the optimum pH and reduce losses of $NH_3$, while also avoiding salinization by the struvite.

In their review of the use of semi-permeable membranes, Zhang *et al* (2024) commented that covering the compost with a semi-permeable membrane of expanded polytetrafluoroethylene protected between two layers of polyester can increase the pH of the heap. This is achieved by absorbing $NH_3$ in the water layer that forms on the underside of the membrane, so reducing acidification associated with volatilisation of $NH_4^+$. While use of a semi-permeable membrane is likely to be outside the scope of low-income household-scale composting, similar advantages could be achieved (although less effectively) by using other cheaper methods to cover the compost, as seen in figure 2(d). These include covering with soil, leaves, wood or straw. The Indian Coimbatore method plasters the heap with mud to prevent nutrient and moisture losses (Misra *et al* 2003). Covering compost heaps with leaves or soil is commonly practiced in Nepal and has been demonstrated to conserve moisture, promote aerobic decomposition (ICIMOD 2020b) and control the larvae of harmful insects (Kehrli and Bacher 2004). In a village study in Bangladesh, Naher (pers. comm.) lined and covered compost pits with plastic sheeting and observed increased N content (total N 2.5%) and moisture content (70%) of the final compost.

### 3.3. Moisture content and aeration

The optimum moisture content during compx`osting is 55%–65% (Shilev *et al* 2007); this avoids anaerobic conditions developing, which result in slower decomposition due to lack of oxygen, and very dry conditions, which limit microbial growth due to lack of water. Misra *et al* (2003) recommended that, in practice, the pile should start with a moisture content of 50%–60%, falling to 30% when composting is complete. This can again be achieved using co-composting to account for the moisture content of the materials (table 1; figure 2(b)), combining very wet feedstocks (such as bioslurry) with drier materials (such as straw), and watering the heap if the materials are too dry to maintain the moisture content. The moisture content of the co-compost can be calculated by equation (4).

$$P_{w,Co} = \frac{(M_{F1} \times P_{w,F1}) + (M_{F2} \times P_{w,F2})}{M_{F1} + M_{F2}} \tag{4}$$

where $P_{w,F1}$, $P_{w,F2}$, $P_{w,Co}$ are the moisture contents of feedstocks 1, 2 and the co-compost, respectively (%).

For dry feedstocks, the compost can be produced in a shallow pit to avoid the drying action of the wind and sun (Misra *et al* 2003). For wetter feedstocks, high lignin materials, such as straw used for bedding, increase the porosity and aeration of the compost heap. Therefore, in passive composting with no turning, it is recommended that bedding and manure should be mixed in approximately equal volumes and the size of the heap should be limited to 2 m high and 4 m wide to avoid anaerobic conditions developing (NRAES 1992, Misra *et al* 2003).

Heaps can also be aerated to maintain the oxygen requirements of micro-organisms, and this has high potential to increase the subsequent rate of composting. A number of different low-cost approaches have been used to do this. Pipes can be inserted into the heap to increase aeration; the Chinese rural high temperature composting method increases aeration by inserting bamboo poles into the heap and then removing them a day later (Misra *et al* 2003), as seen in figure 2(e), while passively aerated wind-rows embed open ended perforated pipes throughout the pile to increase air-flow (Misra *et al* 2003), as seen in figure 2(f). Aeration can be increased by building the heap in a walled box instead of a pit, as seen in figure 2(g). The compost can also be constructed above the ground to improve aeration at the bottom of the heap (figure 2(h)); the Ecuador on-farm composting method achieves passive aeration by building the heap on a lattice of branches (Misra *et al* 2003), while the Philippines rapid composting method builds the compost on a platform that is 30 cm above the ground (Misra *et al* 2003).

Turning the heap is another way to increase aeration. The Indian Bangalore method, which includes no turning, has a composting time of six to eight months (Misra *et al* 2003). This is reduced to four months with one turn in the Indian Coimbatore method and three months with three turns in the Chinese rural high temperature composting method (Misra *et al* 2003). With daily turning in the Berkely rapid composting method, composting requires only two weeks (Misra *et al* 2003). However, increasing the frequency of manual turning also increases the labour requirements, so methods have been developed to facilitate this. Innovations include a rotary drum composter, which is a closed drum containing ducts for aeration that allows the compost to be agitated by turning (figure 2(i)). Regular agitation and aeration greatly increase the rate of the composting process as well as homogenising the composition (Kalamdhad and Kazmi 2009). Furthermore, the closed drum avoids problems with odours and leachate (Kalamdhad and Kazmi 2009) and maintains the moisture content in dry climates. Designs of rotary drum composters suitable for household use in low-income countries can be envisaged, using a simple drum that can be rolled. However, currently, these are not yet widely available or used.

Vermicomposting is another method that can be used to aerate the compost, using (e.g.) *Eudrilus eugeniae*, *Perionyx excavates*, *Eisenia andrei* or *Eisenia fetida* (red wriggler, brandling, tiger) worms (Amuah *et al* 2022), as seen in figure 2(j)). This increases the rate of composting by the multiple actions of the worms, shredding the organic matter, aerating and homogenizing the heap, and adding enzymes and microbes that further speed-up decomposition (Ghorbani and Sabour 2021). Unlike traditional composting, it requires no pile turning, reducing the release of odours. It is suitable for use by smallholder farmers because it can be operated at low cost and small-scale. The worms are usually cultivated in a substrate of cow dung, soil and organic residues, such as food wastes, in shallow, well-ventilated containers, layered with sand, cow dung and biomass. The containers can be constructed out of wood or using bricks. Under optimal conditions, the worms can process nearly half of their body weight in waste daily; every week, 1,000 worms can transform 0.045 Mg of biomass into 0.025 Mg of vermicompost (ICIMOD 2013). The product is composed of nutrient-rich casts containing significantly higher concentrations of N, P and K than a typical soil, and is recommended to be mixed with soil at a ratio of 1:4 by volume for agricultural use (ICIMOD 2013).

Black soldier fly larvae (*Hermetia illucens*) have a similar action to worms. They usually result in faster decomposition than vermicomposting and are able to feed on a wider range of feedstocks, but they require greater care to maintain optimum conditions (Akumah *et al* 2021). The larvae are voracious feeders on a wide range of biodegradable materials (e.g. food scraps, animal manures and agricultural residues) and reduce the waste volume by up to 50%–80% within days (Diener *et al* 2009). The larvae convert organic substrates into larval biomass rich in protein and lipids, while the residual excrement is a good organic fertilizer with high N, P and K content (Lopes *et al* 2022).

### 3.4. Temperature

The optimum temperature at the start of composting is between 35 and 40 °C (Amuah *et al* 2022). The first mesophilic phase in which biodegradable compounds, such as hemicellulose and proteins, are decomposed into amino acids, polyphenols, carboxylic acids and polysaccharides occurs between 15 and 35 °C (Azim *et al* 2018). Heat loss is inhibited by a low surface area compared to the volume or by insulation of the composter. With inhibited heat-loss, the rapid decomposition of organic compounds results in a steady increase in temperature to the optimum temperature for thermophilic micro-organisms (50 °C–70 °C) (Misra *et al* 2003). The thermophilic organisms are then able to decompose more recalcitrant compounds, while the high temperatures also reduce survival of pathogenic organisms (>55 °C) and weeds (>62 °C) (Mehta *et al* 2014, Misra *et al* 2003). As the compounds available for decomposition by thermophilic micro-organisms are used up, the temperature falls back to the mesophilic range, allowing simpler sugars to be further degraded and the compost to mature to form stabilized humic-like substances (Azim *et al* 2018).

Innovations to optimise the temperature for composting include increasing the volume to surface area by piling the compost into a rounded heap and insulating the heap by digging a pit and covering the heap, or by using a thick-walled vessel. In the Indian Bangalore method, a 1 m deep pit is dug with a sloping floor to prevent waterlogging (Misra *et al* 2003), as seen in figure 2(k). Note that in hotter climates, there is a danger that compost heaps over-heat and catch fire (>75 °C), so the optimum volume to surface area differs according to climate (Misra *et al* 2003). In addition, if the heap is too large, there is potential for anaerobic conditions to develop in the centre of the heap, which slows down the process of composting. This can be controlled by reducing the size of the heap and turning (Misra *et al* 2003).

### 3.5. Labour

Labour requirements can be reduced by carefully planning the relative positions of the composter and the materials available for composting. Animal housing can be designed with channels to allow organic wastes to be quickly swept into pits immediately outside (Basnet *et al* 2020), as seen in figure 2(a). This has been applied in preparing low-cost cow-urine enriched cow-dung compost at Sripur, Gazipur, Bangladesh, which has subsequently been applied in dry and wet rice cultivation at the rate of 4.5 Mg $ha^{-1}$ with a saving of 30% urea- N fertilizer (Naher *et al* 2024). Methods are needed to avoid the compost becoming too wet (so slowing decomposition) and to reduce the impact of flies and odours within the animal housing.

In-field composting can also be used to reduce the labour involved in removing crop residues from the field (figure 2(l)). This approach is seen in zero budget natural farming in India, where jiwamritha, an inoculum made on the farm from a mixture of cow dung, urine and sugar, is sprayed on crop residues to increase the rate of decomposition (Smith *et al* 2020). Similarly, in Nepal, an inoculum, known as jholmal (type 1), is prepared using manure, urine, water and jeevatu, a commercially produced consortium of beneficial micro-organisms including lactic acid bacteria, *Azotobacter* species, *Trichoderma* species, phosphate-solubilizing bacteria, potassium-solubilizing bacteria, photosynthetic bacteria and yeast (Bhusal and Udas 2020, Tiwari *et al* 2023). The jholmal can also be mixed in a 1:3 ratio with water and applied every two weeks to enhance soil fertility and promote plant growth (Bhusal and Udas 2020). Dhakal *et al* (2024) has demonstrated a significant benefit of integrating Jholmal with organic fertilizers in enhancing plant nutrition. A variant, known as gitimal, includes leaves that are bitter, spicy, astringent or sour, and is used as a pesticide (ICIMOD 2020c), while another inoculum, known as panchagavya, includes cow dung, urine, milk, curd and ghee with high energy sources, such as unrefined sugar (jaggery), coconut water and bananas, to produce a plant growth promoter (Singh *et al* 2024) and bio-pesticide (Maity, *et al* 2020). Where there are no alternative uses for crops residues, use of such inoculums in the field can reduce the labour of transporting them to the household, while also avoiding issues of nutrient immobilization due to the decomposition during crop growth of high C:nutrient ratio residues, such as rice straw.

In Sidama, Ethiopia, in-field composting is practiced by making multiple small piles of farmyard manure in the field where it is to be used. The pile is left to decompose and dry, before being crushed and spread on the surrounding area (Moges 2008). Similarly, sheet composting layers materials that are to be composted on the soil in the place where the compost is to be incorporated (Amuah *et al* 2022). These approaches may result in losses of N by volatilisation but have the advantage of reducing the work involved in carting the compost to the field. It also avoids the need for a compost heap to be positioned close to the house where it might attract flies.

### 3.6. Improved composting for low-income households

The methods that are most appropriate to improve composting in a particular household depend on the type of feedstock available (the nutrient content, acidity and moisture content of the feedstock), the climate and the availability of labour, water and finances (table 2; Supplementary materials figure S1).

Using the characterisations of feedstocks provided in table 1, the appropriate row in figure S1 can be selected, and the optimum composition of a layered co-compost chosen to maintain the optimum nutrient content (equation (1)), pH (equation (3)) and water content (equation (4)) of the compost. The size of the layers giving the optimum proportions of co-digested materials can be calculated as shown in equation (2).

Depending on availability, ion-exchange materials and microbial inoculums can be added to improve the value of the compost as a fertiliser. Addition of biochar is very effective for high N feedstocks as it reduces losses of N during composting and also increases C sequestration in the soil. However, biochar should only be added to acidic or neutral feedstocks as it tends to be alkaline, so may reduce the rate of composting if the pH is outside the optimum range. Where biochar cannot be used, soil or clay can be used to increase the cation exchange capacity. Ammonia oxidising bacteria can be added to N rich composts that are alkaline, to reduce N losses by volatilisation. Inoculation with bacteria that fix N, solubilise P or mobilise K can be used to increase the N, P or K content of composts with low N, P or K content, respectively.

A range of physical and macro-biological measures can be used to increase the rate of composting and reduce labour. A cover is particularly recommended for alkaline feedstocks with high N content to reduce N losses and can help to maintain the temperature in all composts. A pit can provide insulation and help to contain the compost if the feedstock is wet and unstructured but requires a sloping floor or drainage to avoid the pit becoming anaerobic. If the compost can be mounded into a heap, this can be insulated using a cover or by plastering with mud. Aeration can be achieved in the heap using aeration pipes (e.g. bamboo), by building on a platform or by turning (e.g. using a rotary drum). For wetter feedstocks, high lignin materials, such as straw, can be added to create aeration channels in the compost. Vermicomposting can be used to greatly increase decomposition in drier feedstocks with low N content; for higher N content feedstocks, composting with black soldier fly is recommended. For wet feedstocks, channels can be used to reduce labour of moving the feedstock to the compost pit, while for drier feedstocks, the convenience of the location for processing should be carefully considered.

**Table 2.** Decision table for methods to improve composting for low-income households.

| | | | | | Does this factor limit use? | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Range | Description | Mitigation approaches | Effectiveness | Finances | Feedstock | Labour | Water |
| C:N | <25 | Excess N | Co-compost with high C:N feedstock or turn-in during composting (1) e.g. rice straw | High | | Yes | | |
| | | Overheating of compost | Absorb nutrients using biochar, carbonate, clay minerals or coir dust | Medium | | Yes | | |
| | | Smells of ammonia | Add ammonia-oxidising bacteria (*Bacillaceae*) | Low | Yes | | | |
| | **25–35** | Ideal range | | | | | | |
| | >35 | Too little N | Co-compost with low C:N feedstock (2) e.g. poultry manure or bioslurry | High | | Yes | | |
| | | Compost does not heat up | Collect urine and apply to compost | High | | Yes | | |
| | | | Co-compost with N-fixing under-utilised wild plants | Medium | | | | |
| | | | Add commercial inoculum of N-fixing bacteria (*Achromobacter*, *Alcaligenes*, *Caulobacter*, *Klebsiella*, *Pseudomonas*, *Stenotrophomonas*, *Xanthomonas*) | Medium | Yes | | | |
| | | | Add commercial *Trichoderma* inoculum | Medium | Yes | | | |
| | | | Inoculate with liquid from the bottom of the compost pit | Low | | | | |
| C:P | <50 | Excess P | Co-compost with high C:P feedstocks (3) e.g. rice straw, barley straw | High | | Yes | | |
| | | Algal bloom in runoff | Absorb nutrients using biochar, carbonate, clay minerals or coir dust | Medium | | Yes | | |
| | | Plants have yellowing leaves & small roots | | | | | | |
| | **~50** | Ideal range | | | | | | |
| | >50 | Too little P | Co-compost with low C:P feedstock (4) e.g. poultry manure | High | | Yes | | |
| | | Compost does not heat up | Mix with rock phosphate | High | Yes | | | |
| | | Plants have reduced flowering & purple leaves | Inoculate with commercial P-mobilizing bacteria (*Aspergillus*, *Bacillus*, *Arthrobacter*) | High | Yes | | | |
| pH | <5.5 | Too acidic | Co-compost with high pH feedstock (e.g. cattle manure) while also adjusting C:N to ideal ratio ~30 | Low | | Yes | | |
| | | Compost does not heat up | Add lime | High | Yes | | | |
| | | Sour smell | Add wood ash | Medium | | Yes | | |
| | | Abundance of fungi | Cover compost | Low | Yes | | | |
| | **5.5–8.5** | Ideal range | | | | | | |
| | >8.5 | Too alkaline | Co-compost with low C:N feedstock (2) e.g. poultry manure or bioslurry to increase acidifying processes | High | | Yes | | |
| | | Compost does not heat up | Turn-in acidic feedstocks (e.g. food-waste, pine needles, citrus peel) | High | | Yes | | |
| Moisture content (%) | <50 | Too dry | Co-compost with wetter feedstocks to achieve the moisture content of 55% (5) (e.g. rice straw) | High | | Yes | | |
| | | Organic wastes do not decompose | Sprinkle compost with water | High | | | | Yes |
| | | Compost does not heat up | Cover compost to reduce evaporation | High | Yes | | | |
| | | | Produce compost in a shallow pit | High | | | | |

**Table 2.** (Continued.)

| Parameter | Range | Description | Mitigation approaches | Effectiveness | Does this factor limit use? | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Finances | Feedstock | Labour | Water |
| | | | Divert urine into compost (take care to avoid excess N or alkalinity) | High | | | | |
| | **50–60** | Ideal range | | | | | | |
| | >60 | Too wet | Co-compost with drier feedstocks to achieve the moisture content of 55% (6) (e.g. most animal manures) | High | | Yes | | |
| | | Organic wastes do not decompose | Increase turning | High | | | Yes | |
| | | Waterlogged | Embed bamboo poles, perforated pipes or construct on a lattice of branches or platform | Medium | | | | |
| | | Smells of bad eggs | Rotary drum composter to increase aeration | High | Yes | | Yes | |
| | | | Vermi-compost or black-soldier fly larvae | High | Yes | | Yes | |
| Initial temperature ( °C) | <15 | Too cold | Increase volume to surface area | Medium | | | | |
| | | Compost does not heat up | Insulate heap (e.g. use a thick-walled vessel or cover with thick fabric) | Medium | Yes | | | |
| | | | Produce compost in a 1 m deep pit with a sloping floor to insulate against low air temperatures | High | | | | |
| | **15–35** | Ideal range | | | | | | |
| | >35 | Too hot | Decrease volume to surface area by spreading heap out to allow heat loss (sheet composting) | High | | | | |
| | | Compost overheats | Turn heap to release heat from the centre | High | | | Yes | |
| | | | Sprinkle with water to cool the heap | Medium | | | | Yes |
| | | | Produce compost in a 1 m deep pit with a sloping floor to insulate against high temperatures | High | | | | |

Abbreviations: C = carbon, N = nitrogen;
[a]See table 1 for examples of high C:N feedstocks and equations (1) and (2) for calculation of layer thickness;
[b]See table 1 for examples of low C:N feedstocks and equations (1) and (2) for calculation of layer thickness;
[c]See table 1 for examples of high C:P feedstocks and equations (1) and (2) for calculation of layer thickness, taking care to also maintain ideal C:N;
[d]See table 1 for examples of low C:P feedstocks and equations (1) and (2) for calculation of layer thickness, taking care to also maintain ideal C:N;
[e]See table 1 for examples of feedstocks with moisture content > 50% (i.e. moisture content = 100 - dry matter content);
[f]See table 1 for examples of feedstocks with moisture content < 50% (i.e. moisture content = 100 - dry matter content).

## 4. Innovations in anaerobic digestion

Anaerobic digestion is the process of decomposition of biodegradable organic materials under low oxygen (usually water saturated) conditions (Kythreotou *et al* 2014). The biogas produced is a flammable mixture of $CH_4$ (50%–70%), $CO_2$ (30%–50%), and traces of water vapour, hydrogen, nitrogen gas and hydrogen sulphide that can be piped into households to provide a low-cost, clean fuel (Idrissa *et al* 2024). Simple digesters running under mesophilic conditions (35 °C–42 °C) have been observed to efficiently convert 69%–80% of the C in the feedstock to biogas (Schievano *et al* 2011), leaving only 20 to 31% of the feedstock C in the residue (bioslurry). However, because the more biodegradable parts of the feedstock are decomposed in the digester, the remaining organic matter is highly stabilised and so will be more efficiently sequestered in the soil. This results in a similar potential for C sequestration from organic wastes applied untreated or as digestate (Smith *et al* 2014a, Lynd *et al* 2024). Furthermore, a high proportion of the nutrients in the feedstock are retained in the bioslurry, with organic matter and P mainly in the solid phase, and N and K mainly in the liquid phase (Maroušek 2013). Therefore, the bioslurry can be used as a rich organic fertiliser that will provide available N and K to immediately improve production in the current crop, as well as enhancing the organic matter content of the soil to improve productivity over the longer term (Smith *et al* 2014a, Smith *et al* 2014b).

Innovations in household biogas digesters are needed to optimise the conditions for anaerobic digestion; as for composting, this includes the C:nutrient ratio, pH, temperature and moisture content. Innovations are also needed to prevent losses of highly reactive N from the bioslurry through leaching and volatilization (Basumatary *et al* 2024) and to ensure the pathogen content of the bioslurry is reduced to safe levels (Chukwu *et al* 2022, 2023). As for composting, innovations are also needed to reduce labour requirements. Cost and water demand are critical factors that determine the feasibility of using anaerobic digestion in low-income households in dry environments (Smith *et al* 2015). Key innovations to achieve optimum conditions for efficient anaerobic digestion are depicted in figure 3.

### 4.1. Carbon to nutrient ratio

The optimum C:N ratio in the feedstock for efficient anaerobic digestion is often quoted as 20 to 30 (e.g. Chatterjee and Mazumder 2019). However, in a more detailed analysis, Idrissa *et al* (2024) suggested that this depends on the type of feedstock, with feedstocks centred around cattle or pig manure having the optimum range of 20 to 35, while the range for chicken manure is 18–22 and for food waste is highly variable. This difference is due to the availability to the micro-organisms of the N contained in the feedstock (Esposito *et al* 2012). In most household digester plants, the main feedstock is cattle or pig manure, so the optimum C:N ratio for low-cost household applications can be assumed to be closer to 20 to 35.

As for composting, the C provides an energy source while the N is used for building cellular structures, so at C:N ratios over the optimum range, the lack of N limits microbial growth, while at C:N ratios below the optimum range, high levels of $NH_4^+$ are released and volatilised to $NH_3$. Free $NH_3$ dissolved in solution has been observed to inhibit methanogenesis leading to complete inhibition at 150 mg $dm^{-3}$ free $NH_3$-N in solution, equivalent to 1700–1800 mg $dm^{-3}$ free $NH_3 + NH_4^+$-N in solution (Yenigün and Demirel 2013, Kumar and Samadder 2020). Therefore, innovations are needed to maintain the C:N ratio within this optimum range, as well as to capture the $NH_3$, which might lead to inhibition of methanogenesis.

Feedstocks can again be mixed (co-digested) to adjust the C:nutrient ratio of the main feedstock (table 1, equation (1), figure 3(a)). For anaerobic digestion, this may involve mixing nutrient poor crop residues or compost into the feedstock or adding nutrient rich feedstocks, such as chicken manure, urine or food waste. Because the feedstock is a slurry, it is possible to fully homogenise the feedstocks before they are added to the digester. This has been achieved in household digesters using a range of pre-treatment methods.

Pre-treatments are used to break-up bulky material and break-down structural components, such as lignin and cellulose, making them more available for the first step in anaerobic digestion, the hydrolysis of complex polymers into simple monomers. Rodriguez *et al* (2017) classed pre-treatment methods as mechanical (chipping, grinding, milling or extrusion), ultrasound, microwave, thermal, chemical or biological. Due to the associated costs and access to appropriate solutions, only mechanical, chemical and biological methods show potential for low-cost applications.

Mechanical methods have three actions; they (1) increase the reactive surface area available to the decomposing micro-organisms by decreasing the particle size, (2) increase decomposability by reducing the degree of polymerization and crystallinity of the polymers, and (3) reduce the size of reaction vessel needed by increasing the bulk density (Rodriguez *et al* 2017). The ideal bulk density of the feedstock is 0.6–0.8 g $cm^{-3}$ (Wang *et al* 2016b). Low-cost methods include pounding the feedstock with a pole in the mixing tank and turn-handle chopping of food wastes (figure 3(b)). These methods are labour intensive but have been observed to greatly improve the production of biogas (Rodriguez *et al* 2017).

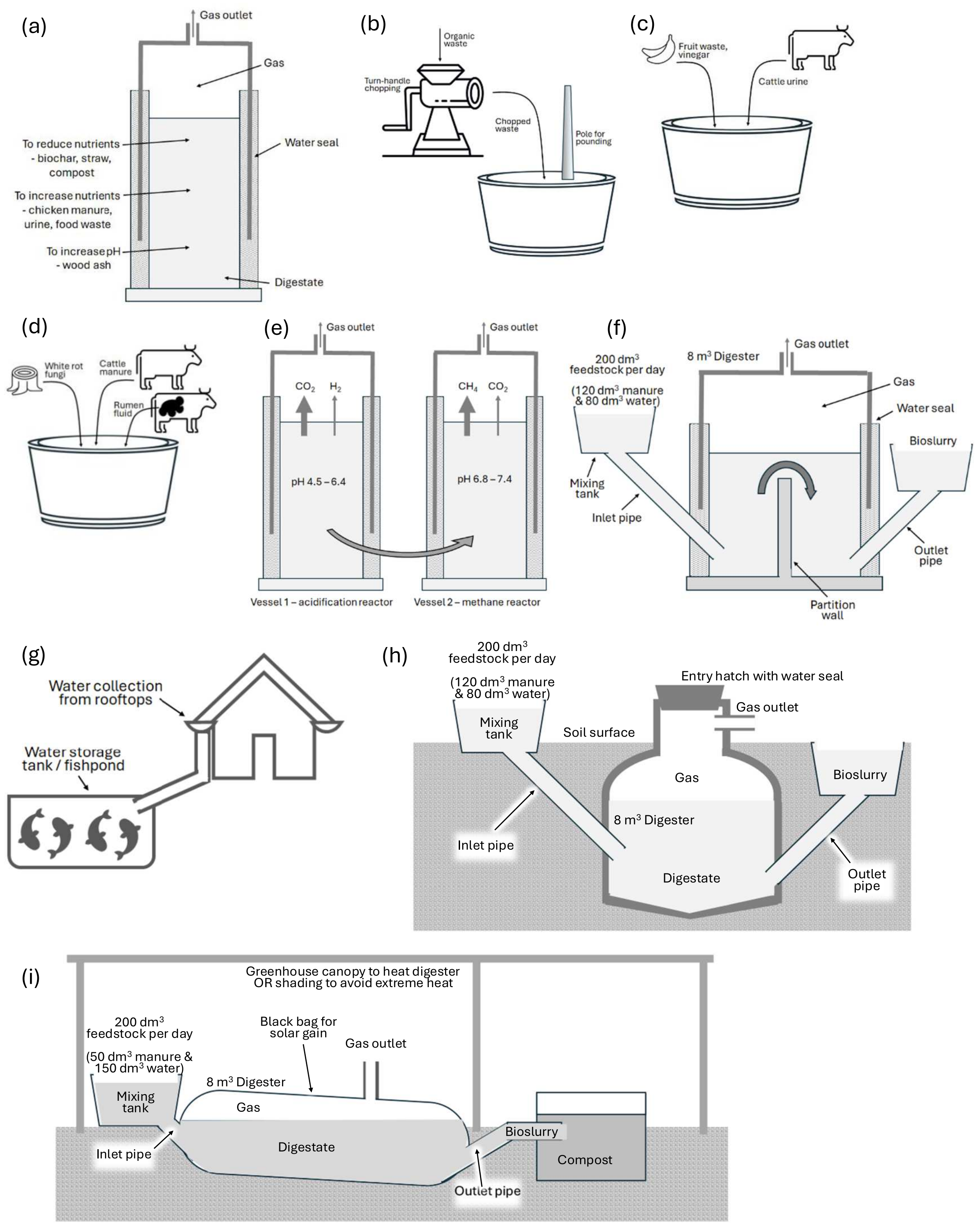


**Figure 3.** Schematic of low cost and labour efficient methods for improving anaerobic digestion; (a) co-digestion to improve nutrient content, pH and water content (e.g. batch digester), (b) mechanical pre-treatment to increase surface area, (c) chemical pre-treatment to decompose recalcitrant compounds, (d) biological pre-treatment to decompose recalcitrant compounds, (e) two-vessel system to maintain optimum pH, (f) adjusting feed-rate to give retention time of ~40 days (e.g. floating drum digester for medium-life and medium cost), (g) rainwater harvesting to meet water demand, (h) underground digester for insulation (e.g. fixed dome digester for long-life), (i) greenhouse canopy to heat the digester and black bag for solar gain, or shading to avoid extreme heat (e.g. flexible-balloon digester for reduced-cost), (j) positioning of digester to reduce workload, (k) combining anaerobic digestion and composting to reduce pathogens.

Chemical methods mainly use acids to break down hemi-cellulose and cellulose, or alkalis to break down lignin (Behera *et al* 2014). This increases solvation and saponification, which breaks cross-linking bonds, increasing swelling capacity and porosity, and allowing diffusion of hydrolytic enzymes into the structure, so facilitating enzyme-substrate interactions (Esposito *et al* 2012). Their feasibility for low-cost applications depends on availability of the chemicals used. Soaking feedstock in cattle urine, which is usually a weak alkali (Richards and Wolton 1976), could be a potential low-cost approach for pre-treating high C:N wastes, such as crop residues; this would both increase the N content and initialise the breakdown of lignin (figure 3(c)).

However, note that the alkalis used are usually stronger (e.g. NaOH, $Ca(OH)_2$, KOH; Stanley *et al* 2022), so further work is needed to establish the efficacy of cattle urine as a pre-treatment. Fruit waste and vinegar are potential on-farm sources of weak acids (citric and acetic acid, respectively) that can be used to initiate breakdown of cellulose (Feng *et al* 2014), as seen in figure 3(c). However, Kikas *et al* (2016) observed that lignin rather than cellulose usually limits biogas production, with reduced biogas yields observed in feedstocks with lignin contents as low as 7.5%. With all chemical pre-treatments, the pH of the feedstock should be neutralised before digestion to avoid the pH of the feedstock inhibiting the process.

Biological pre-treatments attempt to achieve similar partial breakdown of the polymers in the feedstock, either using inoculums of bacteria, fungi or enzymes (figure 3(d)), or using the action of insects that feed on fresh or decaying plant material. However, development of these methods is in early stages and has so far shown limited or inconsistent benefits (Rodriguez *et al* 2017). Pre-treatment by inoculation with white-rot fungi, which is found in decaying wood, has high potential to increase decomposition of lignin (Gao *et al* 2022). Mixed cultures of rumen-derived bacteria have further potential to provide low-cost pre-treatment (Kato *et al* 2008). This could be as simple as mixing straw with the rumen-bacteria contained in cattle manure or rumen fluids obtained from slaughtered animals, but again the approach needs further demonstration. Vinzelj *et al* (2020) investigated the use of anaerobic fungi either cultured or added directly using rumen fluid. These increase the rate of the initial hydrolysis step and have the advantage of being able to continue the breakdown of polymers within the anaerobic digester.

Losses of $NH_4^+$ and the consequent inhibition of methanogenesis by $NH_3$ can be reduced by adding biochar to the bioslurry to absorb the $NH_4^+$ (Khalid *et al* 2021, Kumar *et al* 2021, Song *et al* 2021, Chen *et al* 2023), as seen in figure 3(a). The absorbed $NH_4^+$ is held on the biochar exchange sites and will later be released to the crop when the bioslurry / biochar mixture is applied to the field (Heitkamp *et al* 2021). The biochar may also stimulate anaerobic digestion by providing microsites for micro-organisms, so increasing their density and also their action on the substrate (Khalid *et al* 2021). High concentrations of volatile fatty acids can inhibit methanogenesis if anaerobic digestion is too rapid (Lei *et al* 2021). Biochar has been observed to promote the conversion of volatile fatty acids to $CH_4$, so increasing the stability of the digestion process (Lei *et al* 2021). This may be because the high surface area, pH and porosity of the biochar provide favourable habitats for the methanotrophic bacterial community. Using lab-based reaction vessels, with a feedstock to water ratio in the slurry feed of 1:1, Basumatary *et al* (2024) observed an optimum biochar addition of 15 g biochar per $dm^3$ of slurry feed. Higher doses of biochar should be avoided, as Shi *et al* (2022) suggested there could be an inhibitory effect due to reduced mass transfer and absorption of degradable dissolved organic C by the biochar.

### 4.2. Acidity

There are 4 key stages in anaerobic digestion, involving different cohorts of anaerobic bacteria, facultative bacteria and archaea, each with different optimum pH ranges (Idrissa *et al* 2024).

Bacterial hydrolysis breaks down complex polymers into monomers; sugars, amino acids and fatty acids. At the optimum pH range of 4.5 to 6.4, the reproduction time of the bacteria is usually a few hours, although it can be much longer and become the rate limiting step if the substrate is highly recalcitrant (lignocellulosic compounds) or has a low surface area (Vavilin *et al* 2008).

The next step, acidogenesis, has the same optimum pH range and is a more rapid process that transforms the monomers produced during hydrolysis into volatile fatty acids and alcohols. This process releases $H^+$, so if the supply of monomers is too rapid due to an oversupply of highly biodegradable compounds, the system can undergo a rapid drop in pH.

Acetogenesis converts the volatile fatty acids and alcohols into acetate, $CO_2$ and hydrogen. This is a slow step with a reproduction time of 1 to 4 days at the optimum pH range of 6.8 to 7.5, so it is often the rate limiting step.

Finally, methanogenesis by archaea reduces the acetate and $CO_2$ to $CH_4$, with an optimum pH range between 6.5 and 8.2 (Lee *et al* 2009).

Because the final stages, acetogenesis and methanogenesis, have higher optimum pH ranges than the initial stages, hydrolysis and acidogenesis, the digestion process has high potential to become limited by low pH (Siegert and Banks 2005). Therefore, Mahmudul *et al* (2019) suggested that the optimum pH range for anaerobic digestion should favour the (usually) rate limiting acetogenesis step and remain within the pH range 6.8–7.2. However, it should be noted that this depends on the composition of the organic matter and the community of micro-organisms present in the reactor, so different authors report different optimum pH ranges (e.g. 6.8–7.4; Mao *et al* 2015).

Innovations to optimise the pH range aim to separate out hydrolysis and acidogenesis from acetogenesis and methanogenesis in a two-vessel system (Idrissa *et al* 2024), as seen in figure 3(e). This allows more acidic conditions between 4.5 and 6.4 to develop in the first vessel, before the pH of the digestate is raised to 6.8 to 7.4

in the second vessel to facilitate acetogenesis and methanogenesis (De Cola et al 2024). This has been shown to significantly increase biogas production and the stability of the system, but may not be feasible in low-income households due to the cost of the extra reaction vessel and the materials needed to raise the pH.

As for composting, high pH amendments that could be available for low-income households to maintain the pH of their digesters include wood ash and biochar (figure 3(a)). Depending on feedstock type and production conditions, biochar can be alkaline (Fidel et al 2017), providing an opportunity to both absorb the methanogenesis inhibiting $NH_4^+$ and raise the pH of the digester, so improving biogas production (Kumar et al 2021). More work is needed to develop low-cost digester designs that allow a two-vessel system with addition of biochar or wood ash to the second vessel that is also affordable to low-income households.

### 4.3. Water

The water content affects biogas production by controlling the anaerobic conditions and the time that the feedstock is retained in the digester. This impacts the amount of biogas that can be produced from the feedstock and the quality of the bioslurry residue. Anaerobic digesters can use a batch process, but this requires the labour-intensive process of stockpiling the feedstock, emptying the digester after gas production has stopped, refilling the digester and restarting the digestion process (Rocamora et al 2022). This also results in an interruption in the supply of biogas to the household. Therefore, at household scale, biogas is usually produced using semi-continuous flow digesters, where feedstock is added to one end of the digester, and the bioslurry is pushed out of the other end by the addition of more feedstock (e.g. Mungwe et al 2016, Jegede et al 2019). Therefore, for continuous flow digesters, the ratio of water used determines the volume of material fed in, which controls the length of time that it is retained in the digester.

A simple innovation to improve the production of biogas and the quality of the bioslurry is to adjust the feed rate to achieve the retention time required to produce the most $CH_4$ from the feedstock. The retention time needed depends on the biodegradability of the organic waste; for example, lipids can produce the highest biogas yield but need a long retention time to achieve this, while carbohydrates and proteins degrade more quickly but have lower biogas yields (Esposito et al 2012). Under optimum conditions, for feedstocks such as cattle manure, retention time is usually between 15 and 30 days (Idrissa et al 2024). In sub-tropical / tropical conditions, the retention time is often set to 40 days in order to ensure the digestion is complete (Orskov et al 2014). The feed rate needed to achieve this, $r_{feed}$ ($dm^3$ per day), can be calculated from the volume of the digester, $V_{BD}$ ($m^3$), and the required retention time, $t_R$ (days) as shown in equation (5).

$$r_{feed} = V_{BD}/(0.001 \times t_R) \quad (5)$$

Basumatary et al (2021) investigated the optimum feedstock to water ratio for biogas production from cattle dung and vegetable waste feedstocks, and they concluded that the optimum proportions under both mesophilic and thermophilic conditions are 60 parts of feedstock to 40 parts of water by volume. So, for the example of an 8 $m^3$ household digester requiring a retention time of 40 days, the rate of feed would be 200 $dm^3$ per day, or 9 typical five-gallon buckets. If the feedstock is mixed 60:40 with water (Basumatary et al 2021), the volume of manure required each day would be 60% of this. This is equivalent to approximately five and a half buckets of manure each day mixed with three and a half buckets of water (figure 3(f)). Because organic wastes vary in composition, each household should adjust the feed rate around this norm to optimise gas production for their own conditions. Note that if the typical water content of cattle manure is 80% (table 1), then the water content of the feedstock is $(60\% \times 80\%) + (40\% \times 100\%) = 88\%$ (table 3).

Water is often a key factor limiting uptake of anaerobic digestion (Smith et al 2015). Wardle et al (2021) observed that in rural Ethiopia, water limitation was highly seasonal, with the wet to dry season shift in water availability reducing the likelihood of successful biogas production by 62%. Therefore, innovations are needed to reduce the water requirements and find new ways to meet this demand, especially in dry seasons. Bansal et al (2017) estimated that, to provide sufficient energy for the household by anaerobic digestion, an extra 25 $dm^3$ of water would be required for each person per day. Options for meeting this extra demand include domestic water recycling, rainwater harvesting and aquaculture (figure 3(g)). Bansal et al (2017) concluded that domestic water recycling is insufficient to supply an anaerobic digester in most countries in Sub-Saharan Africa, and should be supplemented with rainwater harvesting, usually from rooftops, using ponds to store the rainwater; these ponds can also supplement income or the protein intake of the family by being stocked with fish.

Other innovations include dry digestion (Wardle et al 2023, Wang et al 2023) and slurry separation to allow recycling of water (Wardle et al 2023). Wardle et al (2023) observed in lab studies that total solids could be increased from 7.4% (50 parts of dung to 50 parts of water by volume) to 10.6% (~70 parts of dung to ~30 parts of water by volume) without detriment to $CH_4$ production. Use of a simple filtering system to recycle bioslurry water back to the digester, such as by passing the slurry through a hessian sack, could further reduce water requirements. Wardle et al (2023) suggested that filtering has potential to reduce water demand by 75%—

**Table 3.** Decision table for methods to improve anaerobic digestion for low-income households.

| Parameter | Range | Description | Mitigation approaches | Effectiveness | Does this factor limit use? | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Finances | Feedstock | Labour | Water |
| C:N | <20 | Excess N | Co-digest with high C:N feedstock or turn-in during composting (1) e.g. rice straw | High | | Yes | | |
| | | Bioslurry smells of ammonia | Absorb nutrients using biochar, carbonate, clay minerals or coir dust | Medium | | Yes | | |
| | **20–35** | Ideal range | | | | | | |
| | >35 | Too little N | Co-digest with low C:N feedstock (1) e.g. poultry manure, food waste | High | | Yes | | |
| | | Low biogas production | Collect urine and add to digester | High | | Yes | | |
| | | | Co-digest with N-fixing under-utilised wild plants | Medium | | | | |
| Bulk density (g $cm^{-3}$) | <0.6 | Low bulk density (1) | Pound feedstocks in the mixing tank | High | | | Yes | |
| | | Feedstock clogs the digester | Chop large pieces of organic waste | Medium | Yes | | Yes | |
| | **0.6–0.8** | Ideal range | | | | | | |
| | >0.8 | High bulk density (1) | Pound with water to disperse | High | | | Yes | |
| | | Low biogas production | | | | | | |
| Lignin (%) | <7.5 | Low lignin (1) | No need for pre-treatment | | | | | |
| | >7.5 | High lignin (1) | Pre-treatment with alkali, such as cattle urine. | Medium | | | | |
| | | Low biogas production | Pre-treatment with white-rot fungi from decaying wood | Medium | | | | |
| | | | Pre-treatment with rumen fluid from slaughtered animals | Medium | | | | |
| | | | Pre-treatment with cattle manure | Low | | | | |
| pH | <6.8 | Too acidic (1) | Co-digest with high pH feedstock (e.g. cattle manure) while also adjusting C:N to ideal ratio ~32.5 | Low | | Yes | | |
| | | Bioslurry smells sour | Add lime | High | Yes | | | |
| | | Low biogas production | Add wood ash | Medium | | Yes | | |
| | | | Add biochar | Mediuim | | Yes | | |
| | | | Two-vessel system - low pH vessel 1, higher pH vessel 2 | High | Yes | | | |
| | **6.8–7.4** | Ideal range | | | | | | |
| | >7.4 | Too alkaline (1) | Co-digest with acidic feedstock (e.g. food-waste, pine needles, citrus peel | High | | Yes | | |
| | | Low biogas production | Two-vessel system - low pH vessel 1, higher pH vessel 2 | High | Yes | | | |
| Moisture content (%) | <85 | Too dry (1) | Co-digest with wetter feedstocks to achieve the moisture content over 85% (5) (e.g. rice straw) | High | | Yes | | |
| | | Low biogas production | Add more water | High | | | | Yes |
| | | | Divert urine into digester (take care to avoid excess N or alkalinity) | High | | | | |
| | | | Domestic water recycing | Low | | | | |
| | | | Rainwater harvesting | Medium | Yes | | | |
| | | | Filter bioslurry and recycle water back to digester | High | | | | |

**Table 3.** (Continued.)

| | | | | | Does this factor limit use? | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Range | Description | Mitigation approaches | Effectiveness | Finances | Feedstock | Labour | Water |
| | **85–95** | Ideal range | | | | | | |
| | >95 | Too wet (1) | Co-digest with drier feedstocks to achieve the moisture content below 95% (6) (e.g. most animal manures) | High | | Yes | | |
| | | Low biogas production | | | | | | |
| | | Retention time less than 40 days | | | | | | |
| Temperature ( °C) | <35 | Too cold | Build digester underground | High | Yes | | | |
| | | Low biogas production | Insulate digester (e.g. with crop residues, leaves, red soil, clay or charcoal) | Medium | | | | |
| | | | Solar water heating system | High | Yes | | | Yes |
| | | | Solar gain using a greenhouse canopy | Medium | Yes | | | |
| | | | Solar gain using a black bag | Low | | | | |
| | **35–42** | Ideal range | | | | | | |
| | >42 | Too hot | Build digester underground | High | Yes | | | |
| | | Low biogas production | Shading to avoid direct sunlight | Medium | | | | |

Abbreviations: C = carbon, N = nitrogen; (1) See table 1 for feedstock characteristics.

100%. Note that semi-continuous flow systems require a liquid slurry to avoid the digester becoming blocked, so one disadvantage of dry digestion is the extra labour required for batch processes.

### 4.4. Temperature

While anaerobic digestion is more rapid under thermophilic (45 °C–60 °C) than mesophilic (35 °C–42 °C) conditions, thermophilic digestion usually requires input of costly heat energy. In addition, development of inhibitory conditions, such as low pH, or high concentrations of $NH_4^+$ or volatile fatty acids, is more likely to occur during the more rapid reactions occurring at higher temperatures, making the process less stable (Weiland 2009). Therefore, household digesters are usually mesophilic (Khalid *et al* 2011).

A stable digester temperature is important for maintaining balance in the digestion stages (Jain *et al* 2015). Depending on the ambient temperature, methods used to improve temperature control include improved insulation, capturing solar energy by heat exchange, or reducing solar gain using shading (Lohani *et al* 2024), as seen in figure 3(i). Improved insulation can be achieved by coating the digester with locally available insulating materials, such as red-mud or charcoal (Yadvika *et al* 2004), by packing crop residues, straw or leaves around the digester (Issahaku *et al* 2024) or by building the digester underground (Kanwar and Guleri 1994), as seen in figure 3(h). Solar energy can be captured using heat exchange from hot air circulating around a bed of stones packed around the digester (Igoud *et al* 2009) or by circulating hot water around the digester (Gupta 2009, Ali and Al-Sa'ed 2018). However, these approaches increase complexity of the system and so can also increase the cost and likelihood of malfunction. Simpler solutions that have been used to achieve solar gain include a greenhouse canopy or a black bag (Mutungwazi *et al* 2020, Gaballah *et al* 2024).

### 4.5. Labour

Labour is another key factor limiting the feasibility of anaerobic digestion in low-income countries (Hamid and Blanchard 2018). If anaerobic digestion greatly increases labour requirements on the farm, many households will not have the capacity to run the digester. Labour requirements may be reduced by less time being spent on collecting domestic fuel, but this is weighed against potential increases to labour due to more time being spent on water collection, slurry mixing and pre-treatment, making and transporting slurry and composts to the fields, and transporting organic feedstocks to the digester. Orskov *et al* (2014) suggested that anaerobic digestion would only be feasible if time spent collecting wood fuel exceeded time spent collecting the extra water needed; using typical times observed for wood fuel and water collection in Sub-Saharan Africa, they estimated that this required the wood fuel source to be 3–4 times more distant from the household than the source of water.

The design of the digester, as well as the careful selection of the households where digesters are installed, can help to minimise labour requirements and risks of dis-adoption (Lwiza *et al* 2017). Methods to reduce water collection times, such as rainwater harvesting, can be included in the digester design (Bansal *et al* 2017), as seen in figure 3(g). This approach is supported by the findings of a survey in Ethiopia, where farmers commented that rainwater harvesting provided water for the digester without adding to their workload (Wardle *et al* 2021). Using a semi-continuous flow digester reduces labour compared to a batch digester because it avoids the need for stockpiling, emptying, refilling and restarting the digestion process (Marchaim 1992, Jegede *et al* 2019), as seen in figures 3(f), (h), (i). These digesters provide a continuous supply of biogas to the household without the need to stockpile gas for periods when the digester is being emptied. As for composting, positioning the digester so that feedstock can be swept out of animal housing into channels that feed the digester can greatly reduce the workload associated with transporting organic feedstocks to the digester. Positioning the digester close to the place where bioslurry is to be used also reduces labour; in some cases, transport of bioslurry to the fields is limited by availability of containers to carry the bioslurry, as jerry cans are reserved for transport of drinking water so must be kept clean (Wardle pers. comm.). Filtering the bioslurry to allow water to be recycled to the digester also reduces the volume of the bioslurry that must be transported to the field, so further reducing labour.

### 4.6. Pathogens

Pathogen deactivation is highly dependent on temperature, pathogen species and retention time in the digester. Manser *et al* (2016) estimated 40% deactivation of the human pathogen, *Ascaris suum*, in mesophilic household digesters after 15 days retention, compared to 73% deactivation after 45 days retention. The deactivation also differs between pathogens. Manyi-Loh *et al* (2014) observed 90%–99% reduction in *Campylobacter sp.* after 18 days while *Escherichia coli sp.* required 62 days and *Salmonella sp.* required 133 days to achieve the same reduction.

A two-stage digester (figure 3(e)), consisting of a separate acidogenic and methanogenic phase was found to provide more effective deactivation of enteric bacterial pathogens (*Salmonella typhi*, *Shigella dysenteriae* and *Vibrio cholerae*) due to the acidic conditions that developed in the acidogenic stage (Kunte *et al* 2004).

Dry anaerobic digestion has also been found to be effective in reducing pathogen loads even at low temperatures of 20 °C and 28 °C, with *E.coli*, *Streptococcus* and *Klebsiella* being reduced by 98%–100% using cow dung substrate (Rajagopal *et al* 2019). However, a wide range of findings have resulted from studies with different types of anaerobic digesters and substrates, meaning caution should be taken when handling and using digestate material. A recent meta-analysis found that while the pathogen content of bioslurry from thermophilic digesters tends to meet European and USA safety standards, bioslurry from mesophilic and psychrophilic digesters does not (Alvarez-Frage *et al* 2025). This suggests that household systems in low-income countries are more at risk than high-input industrialised systems. The study also found that common pathogenic *Clostridium spp.* had strong resistance to anaerobic digestion.

Efficiency of pathogen deactivation can be increased by combining anaerobic digestion with composting (Chukwu *et al* 2022, 2023), as seen in figure 3(i). This takes advantage of the more rapid deactivation possible under aerobic conditions while also providing biogas (Pandey *et al* 2016).

### 4.7. Cost

There are three basic designs of low-cost anaerobic digesters; fixed-dome, floating-drum and flexible-balloon digesters (Chen *et al* 2012). Fixed-dome digesters (figure 3(h)) are the most robust, with a lifespan of ∼20 years, but are also the costliest design, requiring bricks, cement and a skilled mason for construction. While they are suitable for construction near to cities, transportation of materials makes them less suitable for very remote areas or for poor farmers who may have an investment horizon of less than two years (Martí-Herrero *et al* 2014). A floating-drum digester (a water tank cut so that the top half rises to accommodate gas production), as seen in figure 3(f), is less expensive but still requires a significant investment for low-income farmers. Flexible-balloon digesters (a bag with an inlet and outlets for feedstock and gas), as seen in figure 3(i), are the cheapest design. In Latin America, Garfí *et al* (2014) estimated that the cost for equivalent biogas production by a flexible-balloon digester is approximately half the cost for a fixed-dome digester; this accounts for the higher water requirement of a flexible-balloon digester (1:3 feedstock to water compared to 1:1–1.5:1 usually used for fixed-dome digesters) meaning that a larger digester is required to produce the same amount of biogas. They are less robust and usually have a lifetime of only 5–10 years, but this may be appropriate for a farmer with a lower income who may struggle to maintain livestock over the longer term due to intermittent dips in household finances (Martí-Herrero *et al* 2014). Even with the cheapest design, cost can be prohibitive to poorer households. In order to circumvent the barriers of cost, further measures may be needed, including micro-financing using local and external funds to support initial construction costs and formation of user and industry associations to reduce costs by joint purchasing and facilitating links to finance (Mwirigi *et al* 2014).

A portable biogas digester, such as the modified floating dome digester developed by Mushtaq *et al* (2016) for rural households in Pakistan, enhances cost-sharing among neighbours. In this arrangement, neighbouring households can pool their resources to buy a single digester that can serve different households. Costs can also be minimised by appropriate sizing of digesters according to energy requirements and feedstock availability (Meyer *et al* 2021). Improper sizing of digesters leads to non-optimized costs, with oversized digesters increasing surplus costs and labour, while undersized designs do not meet the requirements of the household, so additional forms of energy must be sourced.

### 4.8. Other aspects of digester design

A low-cost system to increase the quality of the biogas is a simple water trap through which the biogas is forced to bubble. This dissolves $CO_2$ and hydrogen sulphide in the water, increasing the proportion of $CH_4$ in the biogas. This can either be changed daily, or a continuous flow method can be used in which water flows through a pipe from top to bottom and the biogas bubbles up from the bottom to top (Kapoor *et al* 2020). Urine has also been used as a more efficient low-cost solvent for removal of these gases (Kim *et al* 2020).

### 4.9. Improved anaerobic digestion

The methods that are most appropriate to improve anaerobic digestion in a particular household depend on the type of feedstock available (the nutrient, lignin and cellulose content, and the acidity and surface area of the feedstock), the climate and the availability of water, labour and finances (table 3; figure S2).

If the feedstock has a low surface area (i.e. it is in large pieces), pre-treatment by pounding or chopping is advisable, although this is labour intensive and so may not be possible if the household has a limited amount of spare labour available. If the feedstock is high in cellulose, pre-treatment with any available weak acid (such as fruit waste or vinegar) will help breakdown of the cellulose. However, this should only be done if the feedstock is not initially alkaline as this will make it difficult to acidify. Similarly, if the feedstock is high in lignin, pre-treatment with any available weak alkali (such as cattle urine) will help breakdown of the lignin, but this should only be done if the feedstock is not initially acidic. Adding cattle urine is inadvisable if the feedstock has a low C:N ratio (i.e. a high N content) as the increased N content due to urine addition may inhibit the digestion process. In this case, inoculating with white rot fungi can instead be used to break down the lignin. If available, inoculation with rumen fluid will further facilitate breakdown in lignin- or cellulose-rich feedstocks. Following chemical pre-treatment, the feedstock should be neutralised before digestion. The amounts of urine, fruit waste or vinegar needed for pre-treatment and neutralisation can be estimated as shown in equation (3).

Co-digestion feedstocks should be selected to achieve the optimum C:N ratio and pH for digestion (see equations (1) and (3)). Biochar is useful to counter excess N but should only be adopted if the feedstock is acidic or neutral as biochar tends to be alkaline. Excess acidity during digestion can also be remedied using wood ash or lime, if available.

Physical measures to improve the digestion process include adjusting the feed rate to achieve a retention time of ~40 days, as specified in equation (5). Rainwater harvesting and domestic water recycling can be used to make the water required for anaerobic digestion more accessible. If rainfall is limited, dry digestion or recycling of water in the bioslurry could be implemented.

Finally, the value of the bioslurry as a fertiliser can be improved by mixing it with biochar or compost. This provides available nutrients that facilitate the composting process, enriches the biochar with nutrients, and reduces losses of available nutrients from the bioslurry.

## 5. Innovations in pyrolysis

Under low oxygen conditions, pyrolysis converts organic wastes into biochar; organic matter with a highly stabilised, aromatic structure that can be used to improve nutrient and water retention and to sequester C in the soil (Atkinson *et al* 2010, Bruun *et al* 2011, Nkoh *et al* 2021, Li and Tasnady 2023). Biochar is produced under low oxygen conditions, usually at temperatures between 300 and 900 °C (Cha *et al* 2016). Pyrolysis is defined as slow (400 to 500 °C at a rate of 0.1 to 1 °C per second for a duration of 300 to 550 s), intermediate (500 to 650 °C at a rate of 1 to 10 °C per second for a duration of 0.5 to 20 s) or fast (850 to 1250 °C at a rate of 10 to 200 °C per second for 0.5 to 10 s) (Tripathi *et al* 2016). The thermochemical degradation reaction involves processes of dehydration, decarboxylation and dehydrogenation, with the nature of products dependent on biomass type, pyrolysis temperature and heating rate (Tripathi *et al* 2016).

Within low-income households, biochar can be produced by slow pyrolysis using a pyrolysis cookstove (Müller *et al* 2019), as seen in figure 4(c), which can provide household energy in the form of syngas while also reducing the emissions of harmful particulates with diameter less than or equal to 2.5 μm ($PM_{2.5}$); this reduction was reported to be ~46% of the emissions from traditional cookstoves by MacCarty *et al* (2010) and ~25% by Cornelisen *et al* (2016). If household energy is not needed, biochar can be produced more cheaply using methods ranging from soil pits (figure 4(a)) to simple kilns (figures 4(b)–(d)) (Namaswa *et al* 2023). Biochar can also be produced centrally in large-scale industrial systems (Panwar *et al* 2019). This uses regional collection of crop residues, and allows controlled production, enrichment of biochar with nutrients and sale of biochar-based fertiliser back to farmers (Müller *et al* 2019). Large-scale systems have the advantage of higher quality and consistency of the biochar produced, but they reduce the potential for the energy released to be directly used within the household (Smith *et al* 2023) and farmers remain dependent on external producers for the biochar they use.

Innovations in pyrolysis are needed to provide simple designs to produce 'designer biochar' that maximises the return of C and nutrients to the soil while increasing the positive impacts of biochar applications on the nutrients and water available to plants, as well as improving the soil pH. Innovations are also needed to reduce the cost and labour requirements of biochar production, and to increase the provision of clean energy to households. For biochar producing cookstoves, further innovations are needed to improve thermal efficiency (maximize heat transfer to the cooking pot), and yield efficiency (maximize the amount of biochar produced from a specified amount of feedstock), without compromising the quality of resultant biochar. Key innovations to achieve optimum conditions for efficient pyrolysis are depicted in figure 4.

### 5.1. Carbon and nutrients

According to Bruun *et al* (2011), the retention in biochar of feedstock C ranges from 20% to 50%, with a higher percentage of C retained at lower temperatures (<400 °C) than at high temperatures (up to ~700 °C). However, at lower temperatures, the biochar contains more labile organic compounds, which are susceptible to rapid decomposition in the soil and can result in immobilisation of nutrients during decomposition. Conversely, at high temperatures the biochar is mostly composed of recalcitrant compounds and so is less susceptible to

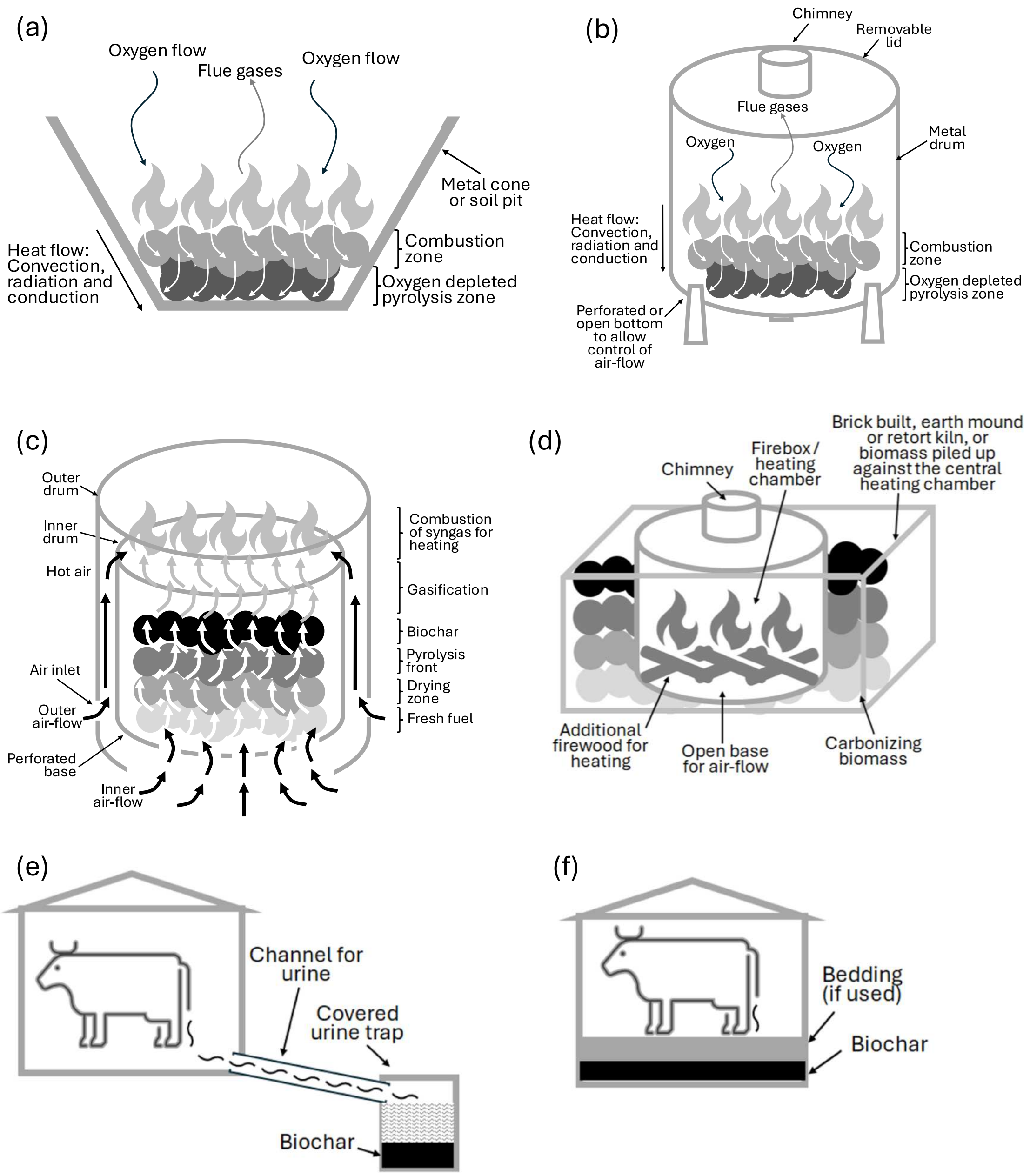


**Figure 4.** Schematic of low cost and labour efficient methods for improving pyrolysis; (a) heat and gas flow in a soil pit, kon-tiki or Oregon kiln (Namaswa *et al* 2023), (b) drum kiln (Namaswa *et al* 2023), (c) top-lit updraft gasifier (Namaswa *et al* 2023), (d) brick-built kiln, earth-mound kiln or retort kiln (Namaswa *et al* 2023), (e) urine trap loaded with biochar to absorb N, (f) spreading biochar on floors of animal housing.

decomposition (Mukherjee and Zimmerman 2013, Nelissen *et al* 2015). Due to this recalcitrance, Smith *et al* (2014a) estimated the C gain in the soil following application of high temperature biochar to be 50%–75% more than if the same amount of feedstock had been applied to the soil as fresh wastes, despite the 20%–50% losses of C during biochar production. Therefore, to increase C sequestration in the soil, untreated wastes should be pyrolyzed, and this is likely to be more effective at pyrolysis temperatures over 400 °C.

However, a key disadvantage of pyrolysis is the potential loss of nutrients from feedstocks (Smith *et al* 2023). For example, N is lost as organic N and $NH_3$ during the thermal decomposition of proteins, protein-like compounds and $NH_4^+$ (Hu *et al* 2017). This can have negative impacts on the atmosphere due to the formation of $NO_x$ gases which can result in acid rain and photochemical smog (Hu *et al* 2017). Biederman and Harpole (2013) observed higher N concentrations in low than in high temperature biochar. However, after the mass losses occurring during pyrolysis were accounted for, Smith *et al* (2023) estimated that N losses were actually greater at low temperatures (up to 99% of the N in the feedstock) than at high temperatures (as low as 55% of the N in the feedstock). However, this finding is highly uncertain, so further assessment is needed of potential methods to retain these valuable nutrients in the cropping system. Nevertheless, because of the high potential for nutrient loss, as a rule, biochar should only be produced from feedstocks with a high C to nutrient ratio. These would be materials that cannot be composted or digested without addition of nutrients (C:N > 40), such as wheat or rice straw, maize cobs or groundnut husks, to avoid these nutrients being wasted. If biochar is produced from nutrient rich materials, such as manures, high rates of nutrient waste are likely.

A potential counter to this is the capacity of the biochar to absorb nutrients and hold them in the soil, allowing more nutrients to be taken up by crops (Smith *et al* 2023). This is particularly beneficial to crop production in tropical soils, which tend to be more highly weathered and so have a lower cation exchange capacity and are less able to hold nutrients than temperate soils (Jeffery *et al* 2017). Absorption of nutrients depends on the porosity, surface area and the surface charge of the biochar. High temperature biochar tends to be more porous and have a higher surface area than biochar produced at lower temperatures due to more complete removal of the labile compounds at high temperatures (Mukherjee and Lal 2014). However, above 650 °C, Jeong *et al* (2016) observed a decrease in surface area due to collapse of the internal structure of the biochar. By contrast, lower temperature biochar tends to be more highly charged than high temperature biochar (both positively and negatively charged) due to the incomplete formation of recalcitrant bonds (Novak *et al* 2009a,b). Therefore, the potential of low and high temperature biochar to absorb nutrients, such as N, is highly variable. In general, high temperature biochar absorbs less N than lower temperature biochar (Karim *et al* 2022), but this is not always the case (Smith *et al* 2023).

As already discussed, biochar can be enriched with nutrients by adding it to composts (figure 2(b)) or mixing it with $NH_4^+$ rich bioslurry (figure 3(a)), acting to retain more nutrients in composts so improving their quality, and to separate $NH_4^+$ from the liquid bioslurry so reducing inhibition of methanogenesis by $NH_3$. It can also be used directly in the farming system to absorb nutrients that would otherwise be lost in runoff, such as N lost as urine-runoff from animal housing (Smith *et al* 2023). This might be done through a urine trap that is loaded with biochar to absorb N (figure 4(e)), or by simply spreading biochar on bare floors in animal housing or under livestock bedding (figure 4(f)). Smith *et al* (2023) estimated that in 2020, biochar produced from crop residues that would otherwise be burnt in the fields in India had the potential to retain 67% of the N lost as nitrogen oxides ($NO_x$) and $NH_3$ from India's energy, industry and farming sectors; this is equivalent to 31% of the N that was applied to farmland across India as synthetic fertiliser. To achieve this, farming and production systems would need to be re-designed to facilitate the production and use of biochar from any crop residues that would otherwise be burnt. For example, this might entail centralised collection of crop residues and use to produce enriched biochar that is sold back to farmers as a low-cost fertiliser, collective production of biochar at a larger kiln located within the village, or household production of biochar from crop residues used to soak up cattle urine from housing and then applied directly to crops. More work is needed to establish the feasibility, efficacy, labour requirements and cost-effectiveness of such management changes.

### 5.2. Water

Because energy is required to drive off water from the structure of crop residues, pyrolysis is more efficient if done with dry materials; Joseph and Taylor (2024) suggest that the moisture content of materials entering the kiln or cookstove should be less than 20%, ideally ~15%, and that materials with a moisture content of 40%–50% are unsuitable for pyrolysis. Therefore, it is important to sun-dry wetter feedstocks before pyrolysis to improve efficiency.

Biochar affects water available in the soil by modifying the structure, hydraulic properties, surface albedo and heat fluxes of the soil (Acharya *et al* 2024). Bulk density and saturated hydraulic conductivity are especially reduced in sandy soils (Acharya *et al* 2024). Water holding capacity is increased due to the hydrophilic nature of the biochar, which is dependent on surface functional groups (Blanco-Canqui 2017). The increased specific surface area provided by the added biochar also increases water holding capacity of the soil; this is dependent on surface area and particle density of the biochar (Blanco-Canqui 2017). In addition, the enhanced porosity associated with the biochar itself, as well as the increased action of soil fauna, further increases water holding capacity (Blanco-Canqui 2017). However, at pyrolysis temperatures over 550 °C, Ghorbani *et al* (2022) observed the biochar to become hydrophobic due to loss of oxygen, resulting in water repellency when the biochar was applied to soils. Therefore, optimum impacts on soil water are likely to be achieved by producing biochar at temperatures below 550 °C.

### 5.3. Temperature

Heat is delivered to the biomass during pyrolysis in three ways; by flame-curtain pyrolysis, by contact with the walls of a firebox, or by recirculating hot combustion gases (Joseph and Taylor 2024). The pyrolysis process involves five key stages (Joseph and Taylor 2024): (1) drying to remove moisture; (2) conditioning (between 150 °C and 180 °C) to remove water that is chemically bound to the structure; (3) torrefaction (between 180 °C and 250 °C) to remove volatile gases, including methanol and acetic acid (known as wood vinegar or pyroligneous acid), so increasing the energy density of the remaining biomass; (4) exothermic pyrolysis (between 250 °C and 400 °C) where the biomass breaks down to release combustible gases, including $CH_4$ and hydrogen (syngas), and produce a C-rich biochar matrix; (5) endothermic pyrolysis and final conditioning (above 400 °C), requiring input of heat to further raise the temperature and release more volatile compounds, producing porous biochar that is high in C. The amount of time spent in each phase of pyrolysis controls the physical characteristics (porosity, charge and nutrient content) of the resultant biochar.

In flame-curtain pyrolysis, the biomass is heated by flames which burn at the top of the biomass and exclude oxygen from the biomass lower in the kiln (Jayakumar *et al* 2023). This method is highly suitable for low-income households as it is simple, both in operation and equipment needed. Flame-curtain pyrolysis can be done with no-cost using a simple soil pit (figure 4(a)), which can be dug in the crop-field to reduce labour of transporting crop residues. Efficiency can be improved at a small cost using a metal cone (e.g. the kon-tiki kiln), a pyramidal dome (e.g. the Oregon kiln) or a drum kiln, which can be perforated or open at the bottom to allow air vents to be used to control the temperature (figure 4(b)) (Namaswa *et al* 2023). Cornelissen *et al* (2016) observed benefits in these methods of easy and cheap construction and operation, avoiding the need for start-up fuel and providing a relatively fast pyrolysis time.

In Nepal, farmers are being trained in the use of soil pit and metal kon-tiki kilns to produce biochar by slow pyrolysis for soil improvement. Vista and Pandit (2023) observed that a soil pit was cost effective and easy for farmers to adopt, and that the biochar produced had a high pH (9.8), 72% organic C, a surface area of 215 $m^2$ $g^{-1}$ and a cation exchange capacity of 72 cmol $kg^{-1}$. On application to the soil, the biochar improved the soil pH, C content, cation exchange capacity, base cations and availability of P and K (Vista and Pandit 2023). However, flame curtain pyrolysis tends to have lower yield than other methods and reaches lower temperatures, resulting in incomplete burning of pyrolysis gases and higher particulate emissions (Namaswa *et al* 2023). Modifications in drum kiln design, such as a fan to force an up-draft, insulation to retain energy or agitation to reduce uncharred zones, can improve the efficiency and consistency of biochar production (Namaswa *et al* 2023), but will add to cost, and provide no means of using the energy released for household applications, such as cooking.

Top-lit updraft gasifiers (figure 4(c)) similarly use flame-curtain pyrolysis but are designed to make use of the energy released for cooking or for other purposes. They can be constructed relatively cheaply using two concentric metal containers (such as recycled metal cans) with holes in the outer container to provide the main air inlet (Birzer *et al* 2013). When the fuel held in the inner container is ignited at the top, it draws an updraft of air through the fuel, so carrying the pyrolyzed gases upwards. Secondary inlet holes in the outer container take air directly up through the space between the inner and outer walls, allowing it to enter the inner container at the top. This air is heated on the way up by contact with the inner wall, so that the flammable pyrolysis gases ignite in the hot air. This efficient burning process delivers heat to any pot placed on top of the stove and reduces the emissions of unburnt gases and particulates. As a result, a top-lit updraft cookstove provides a clean source of household energy, reported by Cornelissen *et al* (2016) to have ~75% less emissions of carbon monoxide, $CH_4$ and $PM_{2.5}$ than traditional cookstoves. However, these stoves produce only small amounts of biochar, so are only suited to small households with limited land requiring biochar.

Traditional brick-kilns, earth-mound kilns and retort kilns (figure 4(d)) heat the biomass using two chambers, a firebox and a pyrolysis chamber, separated from the biomass by a thin, heat conducting wall (Namaswa *et al* 2023). In Laos, rice husk biochar was produced using a simple biochar chamber made from stainless steel with rice husks mounded around the outside (Mekuria *et al* 2014). A total of 83.8 ± 4.2 kg of rice husk biochar per chamber per day was produced with a conversion efficiency of 48.1% ± 2.1% and an average burning period of 14.5 ± 1.0 h (Macedo *et al* 2014). Different designs can be used to increase the efficiency of pyrolysis. Pyrolysis flue gases are recirculated through the firebox, so providing more energy, increasing the speed and efficiency of the process and reducing the emissions (Namaswa *et al* 2023). Insulation further increases efficiency by reducing heat loss (Namaswa *et al* 2023). These kilns usually produce a more consistent quality of biochar but can be costly and the process uses additional biomass to provide the heat, so they are more suited to larger scale, industrial biochar production (Cornelissen *et al* 2016).

### 5.4. Soil pH

In a meta-analysis of 232 global studies, Zhang *et al* (2025) concluded that biochar application had significant potential to increase soil pH, averaging a pH increase of 5.59% globally, depending on soil conditions and the pH of the biochar. The effects of biochar on soil pH depend on feedstock type, pyrolysis conditions, application rate and environmental conditions, but can be significant (Vista and Khadka 2017, Pandit *et al* 2021). Pandit *et al* (2018) measured an increase in soil pH from 4.6 to 5.0 with a moderate application of 15 Mg $ha^{-1}$ and from 4.9 to 5.6 with a high application of 50 Mg $ha^{-1}$. Furthermore, Teutscherova *et al* (2017) observed that biochar had a more long-lasting impact on soil pH than lime. This can be highly beneficial in a soil where productivity is limited by low soil pH (Jeffery *et al* 2017). At higher temperatures, the biochar produced tends to be more alkaline than at lower temperatures (Mukherjee and Lal 2014), with biochar produced between 300 and 500 °C having the most potential to increase soil pH (Zhang *et al* 2025). Zhang *et al* (2025) also noted that the type of feedstock influences the pH of the biochar, with biochar produced from manure having the most positive impact on soil pH. However, note that producing biochar from manure is not recommended due to the high potential loss of nutrients.

### 5.5. Cost and Labour

Robb *et al* (2020) calculated the average abatement cost of biochar in low-income countries and concluded that application of biochar to soil is financially feasible in small-scale production systems. A study in Nepal showed that, depending on the feedstocks used, the cost for the production of biochar ranged from ∼12 to ∼15 Nepali Rupees per kg of biochar (Vista and Pandit 2023). Multiple economic analyses of small-scale systems in Africa have shown that biochar use is, not only feasible, but also profitable when combined with other soil amendments. In a study comparing different rates of synthetic fertiliser and biochar on marketable potato yield, Gebre *et al* (2020) found that increasing rates of biochar application from 0 through to 4 and 8 Mg $ha^{-1}$ increased the net economic benefit for all fertiliser rates tested. Tufa *et al* (2022) found similar results for maize. A longer study on bean production by Kheir *et al* (2023) revealed a negative economic effect of using of biochar and other soil amendments in the first year due to initial costs, but a significant net economic benefit in the following two years.

The most cost-effective methods to produce biochar depend on the requirements of the household. If the household needs to use crop residues as a source of energy, a top lit up-draft cookstove is a cheaper way of providing household energy than anaerobic digestion. However, the amount of crop residues that can be processed in a cookstove is less than in a larger kiln. If labour or time between harvests constrains the removal of crop residues from the fields, within field pyrolysis can be done using a soil pit or a large top-lit updraft gasifier constructed out of metal barrels (Steiner *et al* 2018). Alternatively, mounds of crop residues can be covered with soil and burnt to produce biochar that can be directly incorporated into the soil (Zhou *et al* 2018). However, this also limits the opportunities for energy use and biochar enrichment with nutrients.

### 5.6. Improved pyrolysis

The methods that are most appropriate to improve pyrolysis in a particular household depend on whether the energy produced is needed by the household, the nutrient and water content of the feedstock, the amount of crop residues that must be processed, the finances and labour available for pyrolysis, and the sources of nutrients to enrich the biochar (table 4; figure S3). Because pyrolysis only retains a very small proportion of the nutrients in the feedstock, organic wastes should only be used for pyrolysis if the C:N ratio is too high for anaerobic digestion (C:N > 35). If wastes contain more than 20% moisture, pre-processing of organic waste by air drying is needed to improve the efficiency of the pyrolysis process. If the energy is required by the household, a top-lit updraft cookstove is a good option, but if a large amount of organic waste needs to be processed, a kiln or in-field approach will be a more feasible option, especially if labour is limiting. If finances are not limiting, improved kiln designs including two chambers, recirculation of heat, insulation and fans, make the process more efficient and the quality of the biochar easier to control. The cheapest designs, a soil pit or metal cone, are less efficient and controllable, but make pyrolysis accessible for resource limited households. If a nutrient source is available (such as urine), these kilns allow the biochar produced to be enriched before application in the field. However, this requires additional labour, so if labour or time are especially limiting, covering crop residues with soil to achieve in-field pyrolysis will provide some benefit in the increased ion exchange capacity of the soil reducing nutrient losses, although not delivering additional nutrients.

## 6. Synthesis

A summary of the innovative methods used in composting, anaerobic digestion and pyrolysis that are also suitable for low-income countries is given in table 5, showing the benefits and costs of each. Improving soil health and fertility requires more organic matter to be returned to the soil, more C to be retained and more nutrients to be made available, at the right time, to the growing crops. More organic matter can be returned to the soil by replacing biomass-burning with anaerobic digestion or pyrolysis. Composting can also be used to increase the availability of nutrients to crops and the amount of C retained, but current designs of composters do not allow for the energy released to be used by the household.

Because the residues from these biomass treatments are more recalcitrant than fresh waste, even after accounting for C loss during treatment, similar levels of C will be sequestered by applying digestate as would be sequestered from fresh waste and more C will be sequestered by applying compost or biochar. Innovations aim

**Table 4.** Decision table for methods to improve pyrolysis for low-income households.

| | | | | | Does this factor limit use? | | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Range | Description | Mitigation approaches | Effectiveness | Finances | Feedstock | Labour | Water |
| C:N | <40 | Excess N. Do not use | | | | | | |
| | **>40** | **Ideal range** | Add to compost or bioslurry to capture ammonium | High | | | Yes | |
| | | Low N content | Catch urine in a tank and use soak biochar | High | | | Yes | |
| | | Enrich biochar after pyrolysis | Spread biochar under animal bedding or on floors | Medium | | | | |
| | | | Pyrolysis > 400 °C to retain more C | High | | | Yes | |
| Water | **<20%** | **Ideal range** | | | | | | |
| | >20% | Too wet | Sun-dry before use | High | | | Yes | |
| | | | Pyrolysis < 550 °C to avoid hydrophobicity | High | | | Yes | |
| Energy | | Required by household | Top-lit updraft cookstove | High | Yes | | Yes | |
| | | Not required by household | Mound soil over burning crops residues | Low | | | | |
| | | | Soil pit | Medium | | | Yes | |
| | | | Metal cone or dome | Medium | | | Yes | |
| | | | Brick-kiln, earth mound kiln or retort kiln | High | Yes | | Yes | |
| | | | Top-lit updraft kiln | High | Yes | | Yes | |

Abbreviations: C = carbon, N = nitrogen.

**Table 5.** Summary of the potential impacts of innovations in recycling organic wastes.

| Innovation | Amount of carbon recycled | Stabilis-ation of carbon | Nutrients available to crops | House-hold energy | Water balance | House-hold finance | Labour available on farm each day |
|---|---|---|---|---|---|---|---|
| **Composting**[a] | **—** | **+** | **+** | **0** | **0** | **0** | **—** |
| Co-composting[b] | 0 | + | + | 0 | + | 0 | 0 |
| Co-composting with bioslurry[b] | 0 | + | + | 0 | + | 0 | 0 |
| Add high ion-exchange materials (soil, coir-dust, zeolites, biochar, carbonate)[b] | 0 | 0 | + | 0 | 0 | 0 | 0 |
| Add inoculum of ammonia-oxidising bacteria[b] | 0 | + | + | 0 | 0 | — | 0 |
| Add inoculum of nitrogen-fixing bacteria[b] | 0 | 0 | + | 0 | 0 | — | 0 |
| Add rock phosphate and inoculum of phosphorus solubilizing bacteria[b] | 0 | 0 | + | 0 | 0 | — | 0 |
| Add inoculum of potassium-mobilizing bacteria[b] | 0 | 0 | + | 0 | 0 | — | 0 |
| Add home-made inoculum (e.g. jiwamrita, liquid from bottom of manure pit[b] | 0 | 0 | + | 0 | 0 | 0 | 0 |
| Add lime or wood ash[b] | 0 | + | 0 | 0 | 0 | 0 | 0 |
| Cover with semi-permeable membrane[b] | 0 | + | 0 | 0 | 0 | — | 0 |
| Aerate with bamboo poles or perforated pipes[b] | 0 | + | 0 | 0 | 0 | 0 | 0 |
| Build on platform or lattice of branches[b] | 0 | + | 0 | 0 | 0 | 0 | 0 |
| Manually turn heap to aerate[b] | 0 | + | 0 | 0 | 0 | 0 | — |
| Rotary drum composter[b] | 0 | + | 0 | 0 | 0 | — | 0 |
| Vermicomposting[b] | 0 | + | + | 0 | 0 | — | 0 |
| Black soldier fly[b] | 0 | + | + | 0 | 0 | — | 0 |
| Increase volume to surface area to retain heat and moisture[b] | 0 | + | 0 | 0 | + | 0 | 0 |
| Insulate the heap[b] | 0 | + | 0 | 0 | + | — | 0 |
| Choose position to reduce labour[b] | 0 | 0 | 0 | 0 | 0 | 0 | + |
| In-field composting[b] | 0 | — | 0 | 0 | 0 | 0 | + |
| **Anaerobic digestion**[a] | **+**[d] | **+** | **+** | **+** | **—** | **—** | **—** |
| Co-digestion[c] | + | + | + | + | 0 | 0 | 0 |
| Pounding the feedstock[c] | 0 | + | + | + | 0 | 0 | — |
| Turn-handle chopping[c] | 0 | + | + | + | 0 | 0 | — |
| Soaking feedstock in cattle urine[c] | 0 | + | + | + | + | 0 | 0 |
| Inoculation with white-rot fungi[c] | 0 | + | + | + | 0 | — | 0 |
| Mix with rumen bacteria[c] | 0 | + | + | + | 0 | 0 | 0 |
| Add cultured anaerobic fungi[c] | 0 | + | + | + | 0 | — | 0 |
| Add biochar[c] | 0 | + | + | + | 0 | 0 | 0 |
| Two-vessel system[c] | 0 | + | + | + | 0 | — | 0 |

**Table 5.** (Continued.)

| Innovation | Amount of carbon recycled | Stabilis-ation of carbon | Nutrients available to crops | House-hold energy | Water balance | House-hold finance | Labour available on farm each day |
|---|---|---|---|---|---|---|---|
| Domestic water recycling[c] | 0 | + | + | + | + | 0 | + |
| Rainwater harvesting[c] | 0 | + | + | + | + | — | + |
| Aquaculture[c] | 0 | + | + | + | + | + | + |
| Dry digestion[c] | 0 | — | — | — | + | 0 | 0 |
| Underground digester[c] | 0 | + | + | + | 0 | + | 0 |
| Greenhouse canopy[c] | 0 | + | + | + | 0 | — | 0 |
| Insulation with crop residues[c] | 0 | + | + | + | 0 | 0 | 0 |
| Shading[c] | 0 | + | + | + | 0 | — | 0 |
| Black bag for solar gain[c] | 0 | + | + | + | 0 | 0 | 0 |
| Choose position to reduce labour[c] | 0 | 0 | 0 | 0 | 0 | 0 | + |
| Combined anaerobic digestion and composting[c] | 0 | + | + | 0 | 0 | 0 | — |
| **Pyrolysis**[a] | +[d] | **+** | **—** | **+** | **0** | **—** | **—** |
| Urine trap loaded with biochar[e] | 0 | 0 | + | 0 | 0 | + | — |
| Scatter biochar in livestock housing under bedding[e] | 0 | 0 | + | 0 | 0 | + | 0 |
| Sun-dry wet feedstocks[e] | 0 | + | 0 | + | 0 | 0 | — |
| Soil pit kiln[e] | 0 | 0 | 0 | — | 0 | + | + |
| Kon-tiki kiln[e] | 0 | 0 | 0 | 0 | 0 | + | + |
| Fan-forced up-draft[e] | 0 | + | 0 | 0 | 0 | — | 0 |
| Insulation to retain energy[e] | 0 | + | 0 | 0 | 0 | — | 0 |
| Agitation to reduce uncharred zones[e] | 0 | + | 0 | 0 | 0 | — | — |
| Top-lit updraft cookstove[e] | 0 | 0 | 0 | + | 0 | — | 0 |
| Traditional brick-kilns, earth-mound kilns and retort kilns[e] | 0 | + | 0 | 0 | 0 | — | 0 |
| Within field pyrolysis[e] | 0 | — | 0 | 0 | 0 | + | + |

0 (white) = no effect, + (green) = positive impact, - (red) = negative impact;

[a] Assessed with respect to burning organic wastes for household energy and applying the remaining organic waste to the soil without treatment;

[b] Assessed with respect to composting without the extra innovation;

[c] Assessed with respect to anaerobic digestion without the extra innovation;

[d] Increases due to energy provision reducing the need for biomass burning;

[e] Assessed with respect to pyrolysis without the extra innovation;

[f] Increased finances due to reduced need to purchase fertilisers.

to make better use of the energy in the biomass, while producing organic fertilisers that sequester more C and provide more nutrients to increase crop production.

### 6.1. Optimum conditions

For composting, effective treatment requires a C:N ratio of ∼25 to ∼35 (depending on the lignin content of the organic matter), a C:P ratio of ∼50, a pH of 5.5–8.5, and a water content of 55%—65%, achieving temperatures up to 70 °C during composting. For anaerobic digestion, the C:N ratio should be ∼20 to ∼35, with a pH of 6.8 to ∼7.4, a water content of 90%–93% (Wardle *et al* 2023) and temperature (for mesophilic digestion) of 35 °C–42 °C. For pyrolysis, the C to nutrient ratio should be high (to avoid loss of nutrients), the water content should be less than ∼20% (to maintain efficiency) and the temperature of pyrolysis should be 400 °C–500 °C (to maximize beneficial impacts on C sequestration, pH and nutrient availability in the soil). The innovations that have been developed aim to achieve these optimum conditions to maximise energy provision to the household, while reducing demands on water, finances and labour.

### 6.2. Energy constraints

If energy provision is a key constraint to household wellbeing, anaerobic digestion can be used to provide energy from wet materials with a high nutrient content, such as cattle manure. If feedstocks are dry and low in nutrients (such as rice straw), pyrolysis is a better option.

### 6.3. Mixing feedstocks

Co-digestion can be used to achieve the optimum C to nutrient ratio, acidity and water content for digestion; simple calculations can be used to determine the amounts of available feedstocks that should be mixed to optimise conditions for digestion. If the energy from decomposition is not needed, co-composting can be used in a similar way. Mixing biochar into digesters can absorb excess $NH_4^+$, so avoiding inhibition of methanogenesis by high levels of $NH_3$. Mixing bioslurry into compost can be used to increase the N content of the compost, so stimulating the composting process. Adding urea to biochar can increase the N content of the biochar.

### 6.4. Maintaining pH

The pH of the digester or composter can be maintained by adding lime or wood ash. For composting, covering the compost will reduce the acidifying action of $NH_4^+$ volatilisation. For anaerobic digestion, a two-vessel digester can be used, with pH between 4.5 and 6.4 in the first vessel to favour hydrolysis and acidogenesis, and pH between 6.8 and 7.4 in the second to optimise acetogenesis and methanogenesis; this can greatly speed-up the digestion process.

### 6.5. Pre-treatments

Pre-treatments to improve the effectiveness of digestion or composting include pounding the feedstock, turn-handle chopping, soaking with cattle urine and inoculation with bacteria (e.g. bacteria collected from rumen fluid) or fungi (e.g. white rot fungi from decaying wood, or anaerobic fungi collected from the rumen). Treatment with inoculums can also be used to improve the nutrient content of composts, such as ammonia oxidising bacteria to reduce N losses, N-fixing bacteria to add more N, and P-solubilizing and K-mobilizing bacteria to make more nutrients available to the crops. These can be produced on farm by culturing bacteria (e.g. jiwamrita, jhomal or an inoculum from the bottom of the manure pit) or by multiplying up commercial sources of the inoculum (for example, using molasses).

### 6.6. Water and aeration

If water is limiting, anaerobic digestion may only be feasible if combined with rainwater harvesting, a fishpond for storage, or recycling of water back into the digestate, which adds to the cost. Other options under development for dry digestion have promise for future applications where water is limiting. Aeration is more often the limiting factor in composting, so innovations include inserting bamboo poles or perforated pipes to provide a route for air into the centre of the heap, building the heap on a lattice of branches or a platform, regularly turning the heap (such as in a rotary drum composter), or composting with worms or black soldier flies.

### 6.7. Temperature

Innovations to maintain the correct temperature in composting or digestion include using an underground tank or pit, erecting a greenhouse canopy to warm the reaction vessel, and insulating the tank or heap using crop residues, mud or using a thick-walled vessel. Pyrolysis kilns and stoves can similarly be insulated to reduce energy losses.

### 6.8. Cost and labour

Cost and labour are key factors that may limit uptake of innovations in low-income households. Labour can be reduced by carefully planning the position of the compost or digester and using channels to quickly move organic waste into the tank. In-field composting using inoculums to increase the rate of decomposition of crop residues can achieve rapid decomposition, and in-field pyrolysis can be done using either simple soil pits dug in the field, mobile kilns or covering burning crop residues with soil. Low-cost designs of digesters and pyrolysis kilns are becoming increasingly available and have promise to make these methods more available to low-income households in the future.

## 7. Conclusions

As can be seen in table 5, compared to recycling the organic waste without treatment, composting improves the stabilisation of C and availability of nutrients, but does not increase the amount of C being recycled to the soil and requires more labour. By contrast, anaerobic digestion increases the amount of C recycled as the requirement for biomass burning is reduced. However, anaerobic digestion demands extra water, household finances to purchase the digester and labour. Pyrolysis also increases the amount of C that can be recycled and stabilises it without demanding extra water, but has a negative impact on nutrients available to the crop.

For composting, addition of bioslurry, soil, biochar, home-made inoculums or wood ash, aerating with bamboo or perforated poles, building the heap on a platform and choosing the position and dimensions of the heap are all methods that can be used to increase the rate of composting, and improve stabilisation of C and availability of nutrients without requiring extra in water, finances or labour. For anaerobic digestion, this can be achieved by pre-soaking straw in cattle urine, mixing in rumen bacteria, adding biochar, recycling domestic water, insulating the digester with crop residues, building it underground or using a black bag for solar gain. For pyrolysis, no-cost improvement of nutrient availability can be achieved by absorbing N from urine on the biochar, either by scattering it under animal bedding or by creating a urine trap and loading it with the biochar.

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## Conflicts of interest

None of the authors have any financial or non-financial completing interests.

## Data availability statement

No new data were created or analysed in this study.

## Declarations

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## Ethics approval

No ethics approval is required for this review work.

## Consent to participate

No human participants were included in this review work.

## Consent for publication

All authors have consented for publication of this work.

## Availability of data and material

No original data was generated as part of this review work.

## Code availability

No code was generated as part of this work.

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