



# Indigenous bone fertilizer for growth and food security: A local solution to a global challenge<sup>☆</sup>

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## ABSTRACT

We examine the process of recycling the phosphorus that naturally occurs in animal bones, compare the cost of recycled phosphorus to that of conventional phosphorus fertilizer, and measure farmers' willingness to pay for recycled phosphorus. In our research setting of rural Ethiopia, we reach three conclusions. First, we demonstrate that it is possible to make a suitable pelletized P fertilizer from animal bones. Second, we estimate that the recycled P fertilizer costs 16% to 39% less than importing conventional fertilizer. Third, we find that farmer's willingness to pay for recycled phosphorus fertilizer is the same as that for conventional fertilizer.

With the exception of nitrogen (N), no plant nutrient is as critical to agricultural production as phosphorus (P). Unlike N, which can be pulled from the air through the Haber–Bosch process (Erisman et al., 2008), commercial P fertilizers are derived almost exclusively from mined rock phosphate, which is finite and non-renewable (Vassilev et al., 2013). With global demand for P expected to almost double by 2050, the future availability of rock phosphate is threatened (Chowdhury et al., 2017). P fertilizer shortages challenge food security around the world, particularly in Africa, where the poorest farmers face the highest fertilizer prices and highest rates of food insecurity (Cordell and White, 2014).

In the present paper, we examine the process of recycling the P that naturally occurs in animal bones, compare the cost of recycled P to that of conventional P fertilizer, and measure farmers' willingness to pay for recycled P. Because Ethiopia has the largest collective livestock herd in Africa (Negassa and Mohammad, 2008) and is challenged by

high fertilizer prices and food security concerns (Dorosh and Rashid, 2013), it is an ideal setting to evaluate the feasibility of a circular economy approach to converting bone wastes into P fertilizers. A circular economy approach aims to reduce waste while also making best use of wastes by using economically viable processes to increase their value (Toop et al., 2017). We recover bone P in barrel kilns using pyrolysis, which involves the charring of bones at high temperatures in the absence of oxygen. The charring removes any animal-borne diseases from the bones (e.g., mad cow) and concentrates the P content. Next, we grind the charred bones into a fine dust. Using a starch-water solution as a binder, we form small pellets by agglomerizing the charred bone dust and a binder on an angled rotating disk.

The results demonstrate three key findings. First, we show that it is possible to make a suitable pelletized P fertilizer from animal bones. Chemical analysis of our fertilizer product produced in rural Ethiopia

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shows it contains 31.5% total phosphate. These pellets withstood a battery of post-production quality control tests to ensure that they would be sturdy enough to be bagged and transported in the back of a truck like imported commercial fertilizers (Kibret and Nesin, 2021). In our setting in rural Ethiopia animal bone wastes are a nuisance and often end up in landfills. This process changes the shadow price of bone waste from a negative value (e.g., a slaughter house paying to transport bone wastes to the landfill) to a positive value as the wastes become input for useful fertilizer. Second, we estimate that the recycled P fertilizer costs 16% to 39% less than importing conventional fertilizer. Third, we find that farmer's willingness to pay for recycled P fertilizer is the same as that for conventional fertilizer. Taken together, these findings show promise for reducing the cost of P and increasing access to it by recycling locally available materials. The process could potentially create new non-farm industries and employment built around bone collection and P fertilizer production (Blalock et al., 2022).

The current paper proceeds as follows: Section 1 provides some background on the global P supply. Thereafter, the three sections present the experimentation that led to each of our three findings. Section 2 presents the process of making pelletized P fertilizer, and Section 3 details the costs. Section 4 summarizes the auction results on farmers' willingness to pay for the fertilizer. Section 5 discusses the limitations and challenges of our research, and Section 6 concludes the paper.

## 1. Global phosphorus supply and scarcity

The global annual demand for P inputs is estimated to increase 51%–86% by the year 2050 (Mogollón et al., 2018). In addition, P is a nonrenewable resource with a finite supply. Most commercial P fertilizers are mined in China, Morocco, or the United States. This scarcity raises two concerns. First, the high concentration of the mineable reserves risks geopolitical issues that can cause high prices and volatility. Second, the most accessible P – mineable rock phosphate – can be depleted.

### 1.1. The two-fold phosphorus problem

Supply concentration is the first concern. Although the calculation of mineable reserves changes over time as new discoveries are made, recent estimates report between 73% and 76% (Gilbert, 2009; U.S. Geological Survey, 2021) of the world's extractable supplies are in Morocco, China, and the United States. This producer concentration creates price risks for all countries.

For example, the Chinese government imposed a 135% export tariff on rock phosphate in 2008 with the intention of preserving the country's depleting supply. This unilateral change in export policy contributed to an 800% spike in P prices (Cordell and White, 2011) and contributed to food crises in 47 countries (Chowdhury et al., 2017), along with riots in Africa (Berazneva and Lee, 2013). When P fertilizer prices increase, poor farmers are unable to compete with the farmers in richer countries for the available P supplies and are forced out of the market (Cordell et al., 2009). More recently, the Chinese government has restricted fertilizer exports in response to the COVID-19 pandemic (Bown and Wang, 2022).

The second concern is that global P supply is finite and nonrenewable. Vigorous debate about the life span of remaining rock phosphate yields estimates between 70 and 370 years (Chowdhury et al., 2017; Cordell et al., 2009; Cordell and White, 2014; Van Kauwenbergh, 2010). However, no matter the time left for P yields, as the reserves decrease and demand grows, prices will increase (Chowdhury et al., 2017), making the provision of ample P fertilizer to all who require it more difficult.

### 1.2. Options to mitigate phosphorus scarcity

Concern over the concentrated ownership and global scarcity of mineable P resources has focused attention on how to best manage P resources. The most commonly mentioned idea is an across-the-board increase in P use efficiency (Cordell et al., 2011, 2009; Cordell and White, 2014). Although efficient use would reduce agricultural demand, no global oversight authority has created a mandate to promote and monitor efficiency reforms (Obersteiner et al., 2013). Furthermore, although efficiency could curtail the use of P in wealthier nations, improved P availability in food-insecure nations would offset much of the savings. Of course, efficiency does not increase the supply of available P.

However, a circular economy approach could increase the supply of available P. Unlike the linear economy (take make use dispose), the circular economy (grow make use restore) recycles material flows to increase environmental gains and avoid costs (Barros et al., 2020). One approach to increase the available P supply is recycling it from human and animal wastes (Beardsley, 2011; Powers et al., 2019; Siebers and Leinweber, 2013; Siebers et al., 2014). For example, municipal wastewater (Vogel et al., 2017) and sewer sludge have ample concentrations of P, likely from agricultural run-offs (Adam et al., 2009). Microalgae have been used to recover P from rice mill wastewater (Mukherjee et al., 2015) and eutropic water bodies (Siebers et al., 2019). Others have proposed recovering the naturally occurring P in animal bones (Simons et al., 2014). We build on Simons et al. (2014) and operationalize and cost out the process of recycling P from animal bones.

## 2. Producing P fertilizer from animal bones

We partnered with Jimma University in Southwestern Ethiopia to operationalize the recycling of animal bone wastes into a pelletized P fertilizer. The bulk of this work took place during the academic school year of 2015–2016. The production process involved the following: gathering animal bone waste, grinding the full-sized bones into smaller pieces 1–5 cm in length, charring those pieces in a batch-kiln at about 400 °C, further grinding the charred bone pieces into a fine dust, and pelletizing the dust with a starch-water binder.

### 2.1. Gathering bone wastes

One challenge to scaling up any P fertilizer industry is aggregating the raw material (i.e., animal bones). In Ethiopia, as in other developing countries, some animals are centrally slaughtered in formal abattoirs, while some are locally slaughtered at households, restaurants, butcher shops, and so forth. Generally, larger animals, that is, cattle, are slaughtered at centralized abattoirs, while the smaller animals, that is, goats, sheep, and chickens are slaughtered at or near the point of consumption. When cattle are slaughtered at abattoirs, the carcass, less the head and hoofs, is returned to the owner; this means that the bones are still in the carcass, so when the meat is finally removed, the bones could be in any number of places. Jimma is a city of about 128,000, and the local abattoir estimated that about 50–60 cows are slaughtered daily (Section 5 estimates the total bone availability in Jimma). Based on those estimates, the daily cattle slaughter provided more than sufficient availability of fresh bone for aggregators to collect.

We began a small experiment with about 100 participants to evaluate whether collecting animal bones could be a viable entrepreneurial opportunity for the landless poor (Blalock et al., 2022; Nesin, 2017). However, we underestimated how many bones our participants would collect and terminated the experiment after two weeks of collection due to storage space and budgetary constraints that arose because of the large quantity of bones gathered. In the first week of collection, we received an average of 2,687 kg of bone every day while buying bones for 2.0 Ethiopian birr (ETB) (USD 0.10) per kg. The average transaction size was 164 ETB (USD 8.20), or 82 kg of bone. In the second week,

we reduced the price to 1.25 ETB (USD 0.06) per kg and received an average of 2,095 kg per day, with an average transaction size equal to 143.50 ETB (USD 7.18) or 115 kg of bone. For the current study, we use the curtailed experiment as evidence that dispersed bones can be aggregated by setting a positive price and letting market forces act.

## 2.2. Grinding animal bones

Most bones we received were large, that is, femurs, and had to be ground before charring (Appendix B, Figure S1a). We purchased an industrial strength grinder in Addis Ababa to grind the bones into pieces 1–5 cm in length (Figure S1b). We then charred these bones in a batch-kiln.

## 2.3. Pyrolysis of animal bones in a batch-kiln

We built two pyrolysis chambers from locally available materials, for example, a discarded 55-gallon drum (Figure S2a) and sheet metal (Figure S2b).

We sketched a rough design for a pyrolysis chamber (batch-kiln) and hired a local welder to build it (Figure S3a). We also built a brick housing around the batch-kiln for safety and to keep the heat concentrated on the kiln. The basic process involved inserting the smaller bone pieces into the barrel, sealing it shut, and then starting a fire underneath the barrel (Figure S3b).

We inserted a voltmeter and thermocouple into the chamber to take temperature readings. The maximum temperature what was reached while firing different batches was 450–650 °C, with temperatures normally around 400 °C. The charring reduced the mass of the original bones to 61%–79% of the original bone mass, with a mean of 72%. After cooling, the charred bones were removed from the firing chamber (Figure S4a). For additional details related to the material science of charring bones see [Kibret and Nesin \(2021\)](#).

## 2.4. Grinding charred bones into a fine dust

We used a second grinder, also purchased in Ethiopia, to ground the char into a fine powder (Figure S4b). We made pellets by combining this bone char powder with a binder made of starch water.

## 2.5. Making pellets

The method for making fertilizer pellets is either pan granulation or pan pelletization. Pan granulation consists of spraying a binding solution onto a cascading bed of particles (in our case, charred bone powder). The bone particles were placed on an angled, rotating, disk, which enabled the particles to “snowball”, accumulating mass until reaching a certain size and ejecting from the granulation unit. We imported a shallow tabletop disk-type pelletizer, Mars Mineral model DP-14 Laboratory Pelletizer (Figure S5), from the United States. After formation, the pellets were dried in an oven for 30 to 120 min. See [Kibret and Nesin \(2021\)](#) for details on the pelletizing process, such as the speed and angle of the rotating disk, the rates of adding bone powder and binder, the drying times, and a battery of post-production quality tests. The final P fertilizer pellets are in Figure S6.

## 2.6. Chemical analysis

The nutrient content of fertilizer is most commonly expressed as a sequence of three numbers separated by dashed lines. Each number represents the percentage, by weight, of each of the three primary plant nutrients, N, P, and potassium (K). For example, DAP has the following nutrient content: 18-46-0, meaning it is 18% N, 46% P, and 0% K (see [Appendix A](#) for additional details). We tested our pellets made from bone char at an independent laboratory. Their chemical analysis showed that the pellets were 31.5% P (Figure S7). The most direct comparison would be a phosphorus-only fertilizer such as triple

super phosphate (TSP), however TSP is not available on the Ethiopian market. At the time of our study, the only widely available fertilizers were diammonium phosphate (DAP) and urea. DAP contains N and P while urea only contains N. We can construct a “TSP equivalent” and “DAP equivalent” fertilizer from our product.

Our bone char fertilizer product has a chemical composition of 0-32-0. TSP, DAP, and urea have chemical compositions of 0-46-0, 18-46-0, and 46-0-0, respectively. Based on these ratios, approximately 1.46 kg of bone char fertilizer would contain the same amount of P as 1.0 kg of TSP, and a mixture of 0.39 kg of urea (for N) with 1.46 kg of bone char fertilizer (for P) would provide the same plant nutrients as 1.0 kg of DAP. See [Appendix A](#) for a more detailed calculation of the chemical equivalence of these products.

## 3. Comparing costs of locally sourced versus imported P fertilizer

Having achieved our first goal – describing how animal bone wastes can be converted into pellets of P fertilizer – we move to the second aim: an analysis of the cost-effectiveness of this production process. We begin by presenting the overall costs we encountered in our local production process before then breaking those costs down by stage or production process: bone collecting, converting bone residues into bone char, and granulation and distribution. We then discuss how these costs would be different if we were operating as a formal fertilizer business at scale rather than as a research organization in the proof of concept stage. We recognize that our costs reflect only estimates of costs in other contexts, detailing some of the unknown “real-world” costs in Section 5.

### 3.1. Overall production costs

The detailed costs in producing P fertilizer pellets are shown in [Table 1](#). We present a low- and high-cost scenario based on the quantities of bones we collected and our actual production process ([Blalock et al., 2022](#); [Nesin, 2017](#)). We estimate that locally sourced indigenous P fertilizer could be produced at a lower cost than the equivalent import ([Table 2](#)). A locally sourced “TSP equivalent” with the same nutrient content as 100 kg of TSP would cost 39.49–54.16 USD. This is 16.0–38.8% less than the estimated cost of importing TSP (64.49 USD). A locally sourced “DAP equivalent” (with P from bone char and nitrogen from imported urea) with the same nutrient content as 100 kg of DAP would cost between 56.80 and 71.48 USD, about 4.7–24.3% less than imported DAP (75.00 USD).

### 3.2. Bone collecting costs

To gather raw bones, we rented a small site (50 USD/month) to be a storefront where bone collectors could drop off and be paid for bones. The bones were weighed and temporarily stored in a small structure that used corrugated sheet metal as walls. We paid the storefront staff a total of 400 USD/month. Our largest expense was the payment for bones. For these estimates, we extrapolate our collection efforts out to a month’s time to fall in line with the time period of the other presented expenses.

The lowest price we offered was 6.25 USD per 100 kg of raw bone; at this price, we received approximately 2,095 kg/day. The high price we offered was 10.00 USD per 100 kg of raw bone; at this price, we received approximately 2,687 kg/day. We used these costs, even though it is likely that an ample supply of bone could be procured for prices lower than 6.25 USD per 100 kg ([Blalock et al., 2022](#)). Therefore, in a 20-day work month, we estimate that we purchased 41,900 kg and 53,749 kg at the low and high prices, respectively. Our last cost in securing a supply of bone residues was to transport the bones from the storefront where we were buying the bones to our processing site. We paid 400 USD/month to have a truck regularly come by the storefront, load up the bones, and take them to our processing site. Our total monthly cost for collecting bones and transporting them to our processing site was between 3,469 and 6,224 USD (which is 8.28–11.59 USD per 100 kg of raw bone), here depending on the price offered to sellers.

**Table 1**  
Costs for monthly P fertilizer production using small scale batch-kilns (USD).

	Low Est.	High Est.
<b>Securing Supply of Bone Residues</b>		
Collection Site Rental Costs	50	50
Collection Site Labor	400	400
Bone Residue (payout/month) <sup>a</sup>	2619	5374
<i>Bones Residues (payout USD/100 kg raw bones)</i>	6.25	10.00
Bones Collected (100s kg/month)	419	537
Bone transport to Processing Site	400	400
<b>Total Cost of Bone Residue Collection (USD)</b>	<b>3469</b>	<b>6224</b>
<b>Pyrolysis (converting raw bone to bone char)</b>		
Amortization Batch-Kilns (useful life 36 months)	292	375
Amortization Course Bone Grinder (useful life 36 months)	83	83
Amortization Fine Bone Grinder (useful life 36 months)	111	111
Amortization Grinding Stones (useful life 3 months)	100	100
Processing Site Rental Costs	125	125
Labor at Pyrolysis site	450	500
Wood Fuel Costs <sup>b</sup>	1651	3842
<i>Wood Fuel Cost (USD/100 kg of raw crushed bone)</i>	3.94	7.15
Total Bone Char Fertilizer Produced <sup>c</sup> (100s kg)	302	387
<i>Pyrolysis Percent Yield</i>	72%	72%
<b>Total Cost of Pyrolysis (USD)</b>	<b>2812</b>	<b>5137</b>
<b>Post-Production And Distribution</b>		
Granulating Cost Estimate <sup>d</sup>	626	1100
<i>Granulating Cost per 100 kg finished pellet</i>	0.61	0.84
Labor for Granulation Process	275	275
Amortization - 1 m diameter Pelletizer <sup>e</sup> (useful life 60 months)	167	500
Cost Bagging, Transport, Distribution <sup>f</sup>	1086	1393
<i>Cost Bagging, Transport, Distribution per 100 kg</i>	3.60	3.60
<b>Total Cost Post-production and Distribution (USD)</b>	<b>1878</b>	<b>2993</b>
<b>Grand Total Monthly Cost Bone Char Fertilizer Production</b>		
<i>Total Monthly Output (Bone Char Fertilizer 100s kg/month)</i>	8159	14354
	302	387

<sup>a</sup>Collection rates based on bone collection experiment in Jimma, Ethiopia.

<sup>b</sup>Low and high wood fuel costs taken from the most and least efficient bone charring runs in the field.

<sup>c</sup>In our field runs of the batch-kilns, bone mass was reduced to an average of 72% of the original mass.

<sup>d</sup>Granulation cost estimate (adjusted for inflation) from similarly scaled operation of pelletizing limestone fines [Albert and Langford \(1991\)](#).

<sup>e</sup>The low and high price quotes for one meter pelletizer taken from China- and USA-based companies, respectively.

<sup>f</sup>Cost estimate for transport, distribution, and bagging of fertilizer are taken from [Rashid et al. \(2013\)](#). These costs include loading/unloading, warehousing, rebagging, profit margins for unions, bank fees, administrative costs, insurance, inventory, transport from the central warehouse to cooperatives, profit margins for cooperatives, unloading at cooperatives, and bank interest. Some of these costs may not be applicable to a bone char fertilizer producer; however, we include them to be conservative in our estimates.

**Table 2**  
Cost comparison bone char fertilizer versus imported alternatives.

	Low Est.	High Est.
Farmgate Price per 100 kg of bone char fertilizer	USD 27.05	USD 37.10
Farmgate Price per 100 kg of triple super phosphate (TSP) equiv. <sup>a</sup>	USD 39.49	USD 54.16
Farmgate Price per 100 kg of imported TSP <sup>b</sup>	USD 64.49	USD 64.49
Farmgate Price per 100 kg of diammonium phosphate (DAP) equiv. <sup>c</sup>	USD 56.80	USD 71.48
Farmgate Price per 100 kg of imported DAP <sup>d</sup>	USD 75.00	USD 75.00

<sup>a</sup>TSP-equivalent is 146 kg of bone char fertilizer and has the same P content as 100 kg of imported TSP

<sup>b</sup>TSP is not sold commercially in Ethiopia, so we must estimate a price. Based on [Rashid et al. \(2013\)](#), we calculate an Oromia farm-gate price to world price ratio of 1.65:1 and 1.70:1 for DAP and urea, respectively. The average of these ratios (with rounding) is 1.6713:1, so we take the 2015 world price of TSP (\$385.87/MT, World Bank Commodity Price Data) and multiply it by 1.6713 to get \$644.90/MT or \$64.49 per 100 kg.

<sup>c</sup>The DAP equivalent is 146 kg of bone char fertilizer, and 39 kg of urea and has the same P and N content as 100 kg of imported DAP.

<sup>d</sup>The price of DAP sold at input shops in Jimma town and local farmers cooperatives in 2015 (at the time of our data collection) was 15 ETB per kg. This is equivalent to USD 75.00 per 100 kg using the approximate exchange rate of 20.00 ETB/USD at that time.

### 3.3. Conversion of bone residues into bone char costs

Next, we converted the bone residues into charred bones. We spent about 500 USD/batch-kiln for the purchasing the parts and paying for the labor. Because of the limited capacity of the cooking chamber, a batch-kiln like this can cook batches of about 100 kg of bones at a

time. Another limitation of these homemade kilns is the long cooling time necessary before they can be opened (from the start of the batch to the point where it has cooled enough to open takes about 6–7 h). In our scale-up cost analysis, we consider continuous feed pyrolysis machines with larger capacity without such a lengthy cooling time. For our production scenarios ([Table 1](#)), we need to scale to 21 or 27 batch

kilns (2100 or 2700 kg/day total capacity). We amortize the cost of making the batch-kilns over 36 months (though the usable life could be longer because kilns are metal with few moving parts).

To pack the pyrolysis chambers fully, we crushed the bones prior to charring by using a stone crusher that was operated with a hand-crank. This machine was borrowed from a local stone quarry; however, we estimate that the cost to build one and attach a simple motor would be approximately 3000 USD. The capacity of this machine to crush bones is about 300–500 kg/h; hence one machine would be appropriate for the scale of either scenario that we are pricing out. We amortize this cost over an estimated 36-month useful life.

We used a common, locally available wood fuel (eucalyptus) to fire our batch-kilns. At an industrial scale, a different fuel source (electricity, liquefied petroleum gas, or natural gas) would likely have been more suitable. Wood fuel costs approximately 3.52 USD per 100 kg. We weighed the wood fuel that we used in our actual runs and calculated a wood cost per kg of the raw bone. We assigned the highest batch efficiency we achieved to be the low-cost estimate (3.94 USD/100 kg of raw crushed bone) and our least efficient run for the high cost estimate (7.15 USD/100 kg of raw crushed bone). Moisture and organic compounds are volatilized during pyrolysis, reducing the mass of the bones. The charring also eliminates the risk of spreading bovine diseases such as mad cow. The average yield of charred bones was 72% of the weight of the raw bones.

After charring, we ground the bones into a fine dust before pelletization. We purchased a grinder in Ethiopia to do this, which cost 2000 USD. The grinder has grinding stones that are designed to wear out about once every three months at a cost of 150 USD per grinding stone. The capacity of these machines is about 150 kg/h, which meant that we needed two machines. We estimate a 36-month useful life. We estimate labor costs of 450–500 USD/month, depending on the scenario. Our total monthly cost for pyrolyzing the collected bones was between 2,812 and 5,137 USD (which is 6.71–9.57 USD per 100 kg of raw bone), here depending on the fuel efficiency of the batch kilns.

### 3.4. Granulation and distribution costs

We pelletized charred bone dust into pellets using a 5% starch water binder with a tabletop pan pelletizer (see [Kibret and Nesin, 2021](#) for the details regarding the materials science of the pelletization process). However, we did this in small batches and did not distribute our product to cooperatives or other intermediaries in the fertilizer retail supply chain of Ethiopia. Therefore, for the scenarios we have priced out (i.e., 40,000+ kg of raw bone per month), we use estimates from the literature to calculate the granulation and distribution costs, because they are more appropriate for a larger scale. We also include costs for an industrial-sized pan pelletizer, which would be necessary at this scale.

The smallest sized pan pelletizer categorized for an industrial scale operation has a disk with a one-meter diameter (the tabletop version we used had a diameter of only 12 inches and production capacity of only 10 kg/hour). Given the much larger surface area, the 1 m diameter disk can produce at a much higher capacity (350–400 kg of pellets per hour) than the tabletop model. Therefore, for the scenarios we are costing out, one of these industrial scale pelletizers is necessary. The cost of this machine ranges from 10,000 to 30,000 USD, so we used these two prices as the low and high-cost scenarios. We have amortized the cost of this industrial machinery over 60 months.

We used a cost range of 0.60 to 0.84 USD per 100 kg for the granulation costs of the pellets. This rate includes the cost for the binder and drying the pellets. Although we were able to successfully granulate the bone char dust, we did so at such a small scale (one-off batches, about 50 kg at a time) that using the granulation costs for a large-scale process were more appropriate. Therefore, we used the rates (adjusted for inflation) from a similarly scaled operation for the granulation of limestone fines (crushed limestone with agricultural and commercial

uses) ([Albert and Langford, 1991](#)). We added a labor cost estimate of \$275/month for technicians to run the industrial-scale pelletizer.

In Ethiopia, fertilizers are distributed through an established system of cooperatives and intermediaries, so we must consider the cost of distributing the product within this system. A study of the Ethiopian fertilizer supply chain estimated costs of 3.60 USD per 100 kg for the bagging, transport, and distribution of fertilizers from the central warehouse to field-level cooperatives ([Rashid et al., 2013](#)). Although the costs of transport and distribution for the local fertilizer production process could cost less, because the bones would be sourced closer to the fertilizer end-users' location, we use this estimate ([Rashid et al., 2013](#)) from the central warehouse to be conservative. Our total monthly cost for granulation, postproduction and distribution to the field-level fertilizer cooperatives was between 1,878 and 2,993 USD (6.21–7.73 USD per 100 kg of finished bone char fertilizer).

### 3.5. Costs at scale

We believe the costs we have presented would fall at an industrial scale. [Table 3](#) presents the three highest costs individual line items in our production process. The highest cost categories are payments to bone collectors (32%–37% of the total cost), wood fuel (20%–27% of the total costs), and bagging, transport, and distribution (10%–13% of the total costs). We next consider how these costs would change at a larger industrial scale.

In our experiment, we limited the opportunity to sell bones to about 100 participants ([Blalock et al., 2022](#)). We also only offered two prices (0.0625 USD/kg and 0.10 USD/kg). Although we received fewer bones at a lower price, an industrialist buying from anyone would not limit the number of suppliers. This would create supplier competition that would lower the price. Economic theory suggests that anyone whose reservation wage was met by collecting bones would collect bones. Anecdotally, the participants mentioned that they made 2 to 3 times more collecting bones than they would have earned as construction day laborers, who typically earn 1.00–1.50 USD/day (though this type of work is not available everyday) ([Blalock et al., 2022](#)). Therefore, we conjecture that, in areas of high unemployment (i.e., much of rural Ethiopia), if the opportunity to collect bones was open to all, the price would fall.

The next most expensive component of production was the wood fuel for pyrolyzing the raw bones. One option for a large-scale operation would be a continuous feed pyrolysis machine with a different fuel source, such as electricity, natural gas, or liquefied propane gas (LPG). An open-source design for a continuous feed pyrolyzer is available ([Woolf et al., 2017](#)) and would improve the production process we outlined in many ways. In the scenarios we presented, we were limited by the size of batch-kilns to fire the bones (about 100 kg capacity for each) and by the long cooling times of 6–7 h. A continuous feed pyrolyzer would solve both of these challenges; it is designed to process 250 kg per hour. This means that, in a 20-day work month, operating continuously 10 h per day, the machine could process approximately 50,000 kgs, which is similar to the scenarios we presented. Another benefit of the large-scale continuous feed pyrolyzer is that it is designed to operate on LPG, which would provide a more controlled and steady heat source for running the machine rather than continuously loading wood under the batch kilns. LPG is commercially available in Ethiopia, but we were unable to secure a price quote for a storage tank and servicing for this type of operation. Therefore, we cannot estimate a direct comparison of the costs of fuel wood versus the cost of LPG for the continuous feed pyrolyzer. A more thorough green accounting of the process is left to future research.

The downside to this continuous feed pyrolyzer is its large capital cost (580,000 USD according to [Woolf et al. \(2017\)](#)). The financial viability of a continuous feed pyrolyzer would depend on the time horizon, quantity of bone, ease of usability of LPG versus wood fuel, potential cost savings, and the terms of purchase financing. At this

**Table 3**  
Highest cost line items in production process of bone char fertilizer.

	Low est.	% of total	High est.	% of total
Payments to Bone Collectors (USD)	2,618.75	32.10%	5,374.00	37.44%
Wood Fuel Costs (USD)	1,650.86	20.23%	3,842.41	26.77%
Bagging, Transport, Distribution (USD)	1,086.05	13.31%	1,392.94	9.70%

point, it is unclear how cost would change by adopting a continuous feed pyrolyzer.

The third most expensive cost in production was the bagging, transport, and distribution costs. These costs, which have been taken largely from the literature (Rashid et al., 2013), are meant to mimic the costs to deliver the finished fertilizer to the local fertilizer cooperatives that execute the “last-mile” of distribution in the Ethiopia fertilizer supply chain. One of the major cost components in this calculation from the literature are the transportation costs from the central warehouse to the local-level cooperatives (Rashid et al., 2013). We believe that an industrialist setting up a large bone fertilizer processing operation could reduce these costs by placing the industrial site close to both the bone supply and demand for fertilizer. If such locations could be found (e.g., in large regional towns rather than a centralized location like Addis Ababa), then the transport cost to move the finished fertilizer product would be lower than those we used that were based on Rashid et al. (2013).

#### 4. Farmers’ willingness to pay

Having established our first finding—that the fertilizer can be produced—and the second—that it is cost effective—our last research question focuses on the market viability of our product in Ethiopia. One could imagine a variety of reasons why farmers might be unwilling to purchase recycled P fertilizer. For example, unfamiliarity with the product or customs/traditions about bone reuse could constrain demand. To address this, we conducted a small willingness-to-pay auction to see how farmers would receive our product. Our auction estimated willingness to pay based on our description of the fertilizer and the farmer’s visual inspection of our product rather than based on the farmers’ use of the product. Our goal was to flag any major issues that might make the use of recycled P untenable to farmers. Actual willingness to pay in the long term will, of course, vary on the fertilizer’s performance in the field. We did not discuss with the farmers the potential effect of the non-fertilizer component of the bone char, although calcium and other elements in char could modestly affect crop performance (e.g., our pellets are 28.9% calcium, and calcium is the main ingredient in lime, which is often used to increase the pH of the highly acidic soils in Africa).

##### 4.1. Fertilizer equivalency and auction design

The farmers’ reception to our product could be best measured relative to the fertilizer with which they were already familiar. At the time of our trials, there were no sole-nutrient P fertilizers commercially available in Ethiopia (Rashid et al., 2013). DAP, was the only widely available P fertilizer. The Ethiopian government has started building fertilizer-blending facilities tasked with creating custom blends of fertilizers, such as NPS (nitrogen, phosphorus, and sulfur), to address the specific nutrient deficiencies for major agricultural regions (ATA, 2014). The first facility opened in the Oromia region in 2014, but as of early 2016 (when we conducted our WTP experiments), custom-blended fertilizers were unknown by farmers around Jimma, whom had only ever encountered DAP and urea, a nitrogen-only fertilizer.

Direct comparison of DAP, whose chemical analysis is 18-46-0 (NPK) and bone char fertilizer, whose chemical analysis is 0-32-0, is not possible because DAP contains both N and P, whereas bone char contains only P. If we wish to compare DAP and bone char, we must consider the presence of N and concentration of P.

Urea, a fertilizer widely available in Ethiopia, has a chemical analysis of 46-0-0. For a fair comparison with DAP, we mixed bone char and urea so that it had the same amount and ratio of N and P as DAP. A 1.85 kg bag of mixed fertilizer containing 1.46 kg of bone char and .39 kg of urea would contain the exact same amount of primary plant nutrients (N-P-K) as 1 kg of DAP. We hence call a 1.85 kg unit of this new mixed fertilizer a “DAP equivalent”. TSP, which only has P, is equal to 1.46 kg of bone char, we call this “TSP equivalent”. In the auction, we presented bidders with the option of purchasing DAP, our mixed char-urea “DAP equivalent” and the “TSP equivalent”.

We conducted the auctions in two adjacent kebeles of the Mana woreda, which is located in the eastern section of the Jimma zone, Oromia, Ethiopia. The woreda was less than an hour’s drive from the city of Jimma, though many of the sites visited were only accessible by foot. Mana woreda had a population of approximately 150,000 inhabitants, of which 97% were rural (CSA, 2007). The main cash crops of the area were khat and coffee (ATA, 2014). Government extension workers, called development agents (DAs), and local community leaders identified suitable auction locations and recruited approximately 30 individuals to attend. We paid the community leader a small fee for organizing and recruiting the participants at each auction.

The participants completed an interview about farming practices, fertilizer preferences, and demographic information. Then, the participants were given four bidding slips and 75 Ethiopian birr (approx. 3.50 USD). The participants were told that the money was a fee to compensate them for the time they had taken out from their work schedules to participate in the auction and that they were not obligated to use the money during the auction. This was meant to ensure that the fee only served the purpose of relieving the liquidity constraint often associated with poor farmers, which can lead to lower-bound truncation (“zero” bids) (Beltramo et al., 2015; Morawetz et al., 2011). By referring to the payment as a “fee”, we attempted to avoid the payment being seen as a quid pro quo for which the participants should reciprocate by spending more during the auctions, which would bias the bidding (Loureiro et al., 2003).

The head enumerator read a prepared explanation of the Vickrey second-price auction format.<sup>1</sup> All participants were instructed to simultaneously write their bid on a bidding slip for a fertilizer product, and the individual with the highest bid won the item and paid (out of pocket) the price of the second highest bid (Lusk, 2003; Vickrey, 1961). We allowed time for questions. The auction began with a test round auctioning a bottle of cooking oil to improve the participants’ understanding of the auction and to demonstrate that actual money would be exchanged (De Groot et al., 2011).

The participants were invited to take part in auctions for three different bags of fertilizer containing the following: (1) 5 kg diammonium phosphate (DAP), (2) 7.30 kg bone char mixed with 1.96 kg urea (5 kg “DAP equivalent” labeled as MIX), and (3) 7.30 kg bone char (5 kg “TSP equivalent” labeled as bone char). We formulated the MIX fertilizer so that it would have the same amounts of elemental P and N as DAP. The bag of bone char had the same amount of elemental P as DAP and MIX, but contained no N. Each bag was labeled with the fertilizer name and the number of kilograms of elemental N and P. A detailed script was read at each auction describing the detailed contents of each of the bags of fertilizers.

<sup>1</sup> We chose a Vickrey second price auction over Becker–DeGroot–Marschak (BDM) or take-it-or-leave-it (TIOLI) methods because the former requires the least amount of product and we had limited supplies.

We randomized the order fertilizer products were bid on prior to each auction to ensure that order effects and/or participant fatigue were not biasing the bids (Morawetz et al., 2011). The head enumerator asked the participants to refrain from discussing bidding strategies and amounts until the end. Bidding was performed in silence, and the winner was required to execute the payment prior to the start of the next round of bidding. There were no instances in which the winner refused to pay for the fertilizer.

#### 4.2. Auction outcomes

We sold the three fertilizer products (DAP, MIX, and bone char) in each of the five auctions; 149 farmers attended and consented to be interviewed. Below, we describe the farmers and then analyze their bids.

Nearly all the farmers grew maize as their main crop (97%), with an average farm size of 1.17 ha. Average annual household income was reported as 7394 ETB (approx. 357 USD). Mean reported farm size was slightly below the 1.32 ha average size reported for the Oromia region (CSA, 2013), and household income was below the national average income of 11,101 ETB, or 542 USD for farms of similar sizes reported by Headey et al. (2014). The farmers had a mean of 2.28 cattle and 1.18 sheep or goats.

The percentage of individuals (79%) having contact with development agents at least once per month during the planting season was higher than observed in previous studies (Headey et al., 2014). Leveraging DA and community leader contacts for recruitment was the most likely explanation. Similarly, all but one individual stated that their average annual fertilizer consumption was a non zero number; however, country-wide estimates report that only 19%–53% of land is fertilized (World Bank, 2015; Headey et al., 2014; Rashid et al., 2013). The average farmer in our study purchased fertilizer approximately once every two years, which is close to the most recent reports of the national average using fertilizer, 50%–53% (World Bank, 2015; Headey et al., 2014).

Only 11% of the farmers cited problems accessing fertilizer, but 45% of the participants said that they would pay a premium for fertilizer if it were supplied when it was most needed. The farmers stated a preference for local fertilizers (76%) over imports from China, the source of most chemical fertilizers (Rashid et al., 2013). A slight minority (48%) of the farmers stated they had used alternative soil amendments (like compost).

Only 3% of the respondents were able to name the primary nutrients in either urea or DAP, suggesting a lack of basic technical knowledge. A large majority (89%) said fertilizer is important for improving income, suggesting that farmers understand fertilizer's importance but rely on others (extension workers, university researchers, NGOs) for information on the selection and application of fertilizers.

The auctions had 447 bids that were made (149 participants submitting a bid for each of the three fertilizers), and all bids were non zero. We dropped one individual's bids from the analysis because his bid for DAP was more than 700% the market value (implying that he did not understand the auction set up). The market value of DAP at the time of our auctions was 75 ETB.

Our central research questions are answered in Table 4. First, the average bid amount for each of the three products was greater than zero ( $p < 0.01$ ), showing that the farmers were willing to pay for the bone char-derived fertilizer. Second, there was no statistically significant price difference between the two chemically similar products (DAP (53.70 ETB) and MIX (54.39 ETB)), meaning that the farmers appeared indifferent between bone char-derived and imported P. Additionally, the mean bid for bone char (55.09 ETB) is statistically no different than the products that also include N (DAP and MIX).

**Table 4**  
Willingness-to-pay results (bids in ETB).

Product	Obs.	Mean	St. dev.	Min	Max
DAP	148	53.70*	30.98	5	200
Bone char	148	55.09*	31.04	8	170
MIX	148	54.39*	26.13	10	150

Note: Average bids are statistically significantly greater than zero at the \*  $p < 0.01$  level; the differences between mean bids for each type of fertilizer are not statistically significantly different from each other. The MIX product provides the same quantity of N and P as DAP; however, the P was derived from locally sourced bone char, while the P in DAP was imported.

## 5. Limitations and challenges

In this section, we focus on two of the limitations and challenges the industry might face. A first limitation is our knowledge about whether the supply of animal bones is sufficient to support production. A second limitation is the accuracy of our cost estimates.

### 5.1. Sufficiency of bone supply

The largest aggregator of bones in Ethiopia is the central slaughterhouse in Addis Ababa. We visited the facility and found that it rendered bones into chicken feed. However, we also confirmed that it is the only slaughterhouse with the technology to render animal bones and that it did not accept bones from animals slaughtered elsewhere. Future research could analyze the costs and benefits of rendering bones into chicken feed versus using them to create P fertilizer, but this was beyond the scope of the current study. Assuming that the Addis Ababa slaughterhouse continues to render bones, the most logical place to set up a facility to convert bones into fertilizer would be a large regional city.

We did our proof of concept in Jimma, which has a population of about 128,000. We interviewed the management of the slaughterhouse in Jimma to estimate animal bone supply and found figures in the literature of the bone stock that enters the landfills. The general manager and staff of the Jimma slaughterhouse estimated that they slaughter 50–60 cows and 10–20 sheep/goats daily, but also acknowledged that many animals are slaughtered informally at butcher shops or in the homestead. Typical Ethiopian cattle contain 20–30 kg of bones and sheep about 4–5 kg (Negassa and Mohammad, 2008). Therefore, a broad estimate of the total bones created in Jimma based on these interviews would be 1400–3250 kg/day.

Another way to calculate the bones generated each day is to analyze the bone mass found in municipal waste. One study estimated that 88,000 kg of solid wastes are produced daily in Jimma and that 4.7% of these wastes are bone residues (Getahun et al., 2012). This leads to an estimate of about 4,136 kg/day of bone wastes. Both estimates are of the daily flows and do not account for the stock of bones already present in the environment/landfill. If 4,136 kg of bones enter the waste stream daily, then about 1.5 million kg enter the waste stream annually. Therefore, it is reasonable to assume that there are millions of kg of bones spread across the municipality with varying degrees of accessibility. This suggests an ample stock of raw bone material, and that the aggregation challenge can be solved by putting a price on the bones and allowing market forces to act. The evidence suggests that a fertilizer production industry could work for a city the size of Jimma.

### 5.2. Accuracy of cost estimates

A second limitation is the accuracy of our cost estimates. Although we have done our best to estimate expenses accurately and conservatively, several factors may limit their accuracy. Certain challenges impacted our ability to estimate costs of production, the revenue from sales, and the costs of competing fertilizers.

Production cost estimates face three challenges. First, businesses incur overhead costs, such as insurance and taxes that are too numerous to consider individually. We used the costs from a prior study (Rashid et al., 2013), which included overhead expenses for the fertilizer supply chain in Ethiopia, but actual costs would obviously vary. Second, we purchased materials as researchers, not as profit-minded manufacturers, who would certainly obtain different prices. Third, we cannot precisely say how much economies of scale would reduce expenses.

In terms of revenue, our willingness-to-pay exercise was based on our description of our product and farmer's visual inspection. Farmers' actual willingness to pay will depend on experience in the field and how other factors, such as rainfall, soil health, and market access, affect farmers' profitability of using the fertilizer (McCullough et al., 2022).

Finally, the price of competing conventional fertilizer, which is often subject to substantial political and policy-motivated government intervention in markets, can vary. For example, direct subsidies for imported fertilizers are common across sub-Saharan Africa (Jayne and Rashid, 2013), and the Agricultural Development-Led Industrialization plan of Ethiopia has directly and indirectly subsidized many parts of the agricultural supply chain (Dorosh and Rashid, 2013; Rashid et al., 2013). One idea worth considering would be to reallocate the subsidy element built into the current fertilizer importation supply chain towards supporting an infant bone fertilizer industry. Although further detailed research would be needed, this could potentially create greater economic impacts for the rural non farm economy.

We have done our best to address the above challenges, and believe that our numbers appear promising. However, future research is needed for more precision on costs, and would-be commercial operations should proceed with this caution in mind. Finally, of course, our numbers are for Ethiopia, so their applicability to other economies will vary. Hence, whereas we believe the material science conclusions have strong external validity, the external validity of the economics conclusions to other contexts is less certain.

## 6. Conclusions and discussion

In the present paper, we have examined one possible solution to ease the world's limited supply of P fertilizers. We aggregated geographically dispersed bone wastes and created a pelletized bone char P fertilizer. The bone char fertilizer we produced had lower phosphate content than imported TSP, but still a considerable amount at 31.5% P content. In terms of P equivalence, our TSP equivalent costs 16.0–38.8% less than importing TSP. We also created a DAP equivalent fertilizer by combining locally produced bone char fertilizer with imported urea. This DAP equivalent fertilizer cost 4.7–24.3% less than importing DAP.

We tested initial farmer acceptance of the local bone char fertilizer and found no difference in willingness to pay between imported P and local P derived from animal bones. However, we also found that the farmers were willing to pay the same price for a sole-nutrient P fertilizer (bone char fertilizer) as DAP (despite DAP containing N). This may mean that farmers value P more highly than N. However, a likely alternative explanation is that farmers lack the technical knowledge to understand fertilizers in terms of N and P nutrient values (recall that only 3% of participants were able to name the primary plant nutrients in either DAP or urea). Although further analysis needs to be done regarding the marketability and usability of the fertilizer, along with other complementary factors, our research indicates no obvious barrier to farmer acceptance regarding bone char fertilizer. Earlier work has estimated that the total annual flow of bone produced in Ethiopia would be enough to offset approximately 28%–58% of Ethiopia's annual P fertilizer imports, showing that the benefit of recycling P is large in magnitude (Simons et al., 2014).

Creating a local fertilizer industry would allow developing countries to substitute imported fertilizer for locally made fertilizers therefore

saving money and foreign currency. Further, and perhaps more importantly, this would give developing countries a greater ability to control their own P fertilizer supply and develop their own economy. Fertilizer sovereignty may be especially important as global P supplies dwindle or if global geopolitical events cause unexpected price shocks. Similar analysis of the potential to recycle animal bones or other P-rich waste streams should be done for other countries in sub-Saharan Africa to understand the potential economic value and viability of recycling P to ease fertilizer supply constraints and improve food security more broadly. Our findings show that recycling the P in animal bones is market feasible and could be part of a long-term strategy to increase sub-Saharan Africa food security.

## CRedit authorship contribution statement

**Andrew M. Simons:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision. **Milkiyas Ahmed:** Data curation, Investigation, Project administration, Resources. **Garrick Blalock:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing, Supervision. **Bourcard Nesin:** Data curation, Investigation, Project administration, Writing – original draft.

## Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to <https://doi.org/10.1016/j.foodpol.2022.102396>.

## Appendix A

### A.1. Fertilizer quantity equivalence calculations

The nutrient content of fertilizer is most commonly expressed as a sequence of three numbers separated by dashed lines. Each number represents the percentage, by weight, of each of the three primary plant nutrients, N, P, and K. For example, DAP has the following nutrient content: 18-46-0. The first number in the sequence represents the quantity of N, which is chemically expressed as  $N_2$ . Because  $N_2$  is the elemental form of N, the fertilizer is 18% elemental N. The second number, however, represents the quantity of P expressed as  $P_2O_5$ , which is different from the elemental form, which is chemically expressed as  $P_2$ .

To account for this difference, we must convert  $P_2O_5$  to  $P_2$ . Dividing the molecular weight of  $P_2$  (61.95 g/mole) by the molecular weight of  $P_2O_5$  (141.94 g/mole) results in a conversion factor of 0.44. Therefore, for DAP, which is 46%  $P_2O_5$ , the elemental P content is 20.24% ( $.46 \cdot .44 = .2024$ ). For TSP (0-46-0), the amount of elemental P is also 20.24% ( $.46 \cdot .44 = .2024$ ). The bone char fertilizer we created is 31.5%  $P_2O_5$  meaning it has 13.86% elemental P ( $.315 \cdot .44 = .1386$ ). Therefore, the ratio of elemental P in TSP (.2024) to the elemental P in bone char fertilizer (.1386) is 1.46 ( $.2024 / .1386 = 1.46$ ) meaning that 1.46 kg of bone char fertilizer can be substituted for 1 kg of TSP and that the amount of elemental P will be equivalent.

The nutrient content of urea is 46-0-0, meaning it is 46% elemental N. The equivalent ratio of elemental N in DAP (18%) to the elemental N in urea (46%) is 0.39 ( $.18 / .46 = .39$ ), meaning that 0.39 kg of urea contains the same amount of elemental N as 1 kg of DAP. Therefore, we can combine 1.46 kg of bone char fertilizer (to provide P) with 0.39 kg of urea (to provide N) and it will contain the same elemental amounts of P and N as imported DAP.

## Appendix B. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.foodpol.2022.102396>.

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