

The Production of Indigo Dye from Plants

Nicholas Wenner

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FIBERSHED

Local Fiber, Local Dye, Local Labor



Photos by Paige Green (6) and Kalie Cassel-Feiss (right)

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Abstract

THIS REPORT presents a study of the technical, environmental, and economic factors involved in indigo dye production from *Persicaria tinctoria*, with the aim to support increased farm-scale indigo production in the Northern California fibershed and beyond. Two main approaches to dye production—the compost method and the water extraction method—are presented. The processes are discussed in detail, and particular designs are proposed. These proposed systems are then modeled and compared on economic bases.

For the water extraction and compost systems we propose, we estimate the capital expenditure for planting, harvesting, and dye production equipment to be about \$100,000 and \$150,000, respectively. For water extraction, we expect the system to produce about 66 lbs of 40% purity pigment (26 lbs of pure pigment) per acre, enough to dye approximately 630 lbs of cotton. We estimate the compost system could produce 2615 lbs of 3.2% purity compost (84 lbs of pure pigment) per acre, enough to dye approximately 2,200 lbs of cotton per acre. Compared to water extraction, the compost process could produce about 3.1 times the quantity of pure indigo pigment from a given acreage, or about 3.5 times the dyeing capacity.

At 2.5 acres, we find the break-even price for pigment from water extraction to be about \$190/lb for 40% pure pigment, corresponding to a pure pigment price of about \$480/lb. This price is about 2.2 times that of the compost process, or about 2.4 times the cost for a given dyeing capacity. Given this high cost, we find the production of indigo pigment from the heated water extraction process to be technically feasible but not economically viable. That being said, possible increases in plant and pigment yields could have significant impacts on the economic viability of the water extraction system we propose, and the system deserves continued consideration as maximum yields are reliably understood.

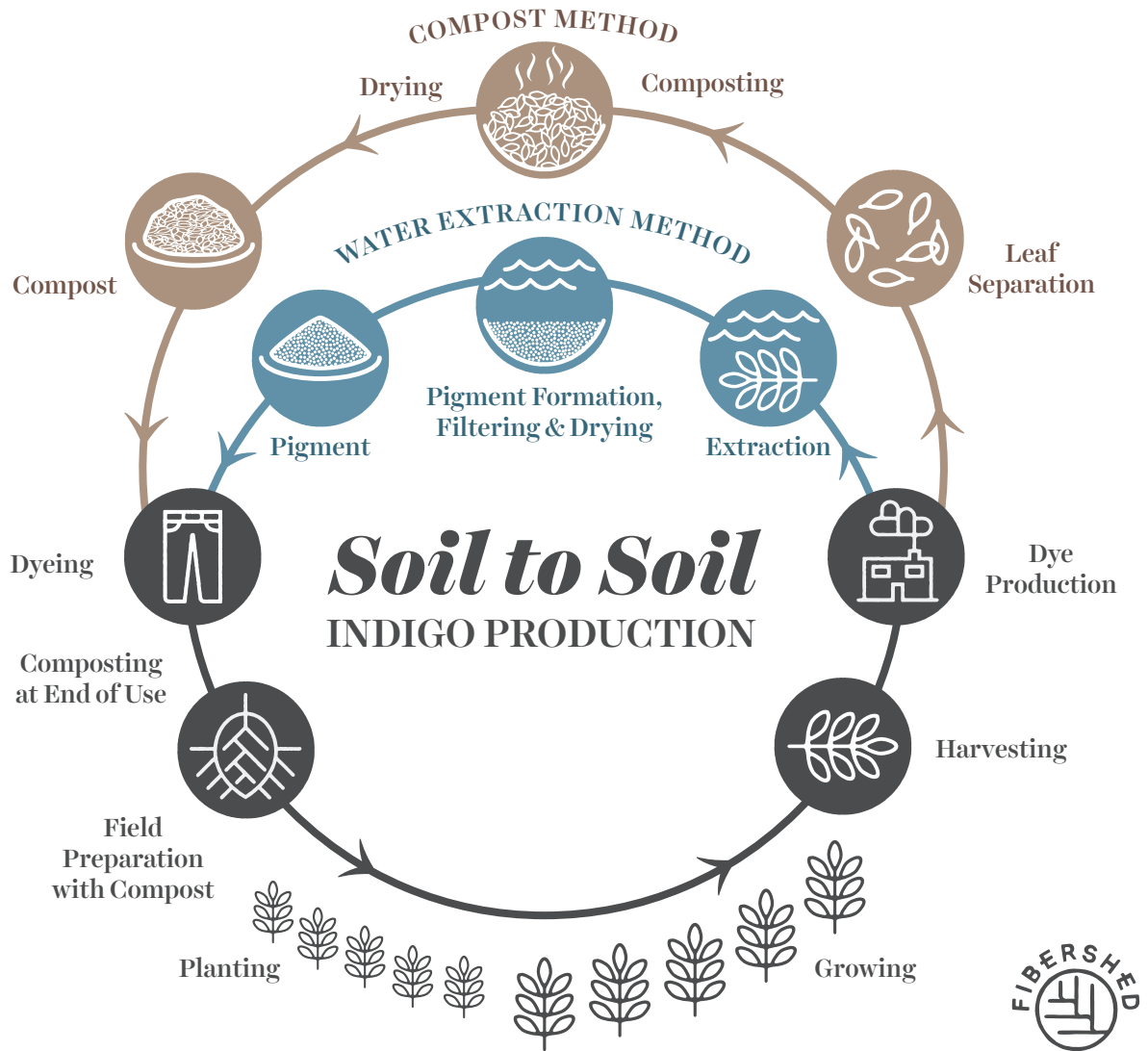
While we do not explore possibilities for fermented water extraction systems in this report, it is possible that such a system would give higher yields and improved economic feasibility compared to the heated water extraction system we propose, and we recommend further research in this direction.

Modeling of the compost system suggests both technical and economic feasibility, with a break-even price for indigo compost of approximately \$7/lb. Modeling production at a scale of 2.5 acres and sales at a price of \$12/lb, we find net profits of about \$32,000 per year at 41% profit margin, translating to earnings of \$54,000 per year when including wages from direct and indirect labor. If all profit was applied to pay back a zero-interest loan on an initial investment of \$150,000, the payback period would be about 4.7 years.

While attractive from a costs perspective, indigo compost may have a significantly smaller market size than pigment, given the greater ease and accessibility of dyeing with pigment. If this limitation can be overcome at scale, demand for natural indigo in Northern California is already ample, with one textile mill expecting to dye enough material to require about 2.5 to 4 acres of indigo if using the compost process.

Considering the global perspective, we estimate that replacing global synthetic indigo production with natural indigo from the compost process would require about 2.1 million acres of indigo, or about 3,300 square miles of production. The price of the natural indigo produced would be more than 80 times that of synthetic indigo.

Natural indigo likely cannot serve as a one-to-one replacement for synthetic indigo in industrial production. That being said, replacing synthetic indigo may not be the most important goal. There are significant impacts to be made by shifting culture and our patterns of production and consumption. Indeed, part of that shift would be bringing production home and paying for its true costs. We envision a future where communities are supported and clothed in part through the local production and use of natural indigo dyes, and in this report we aim to provide a foundation for that vision, and to outline and explore the paths toward it.



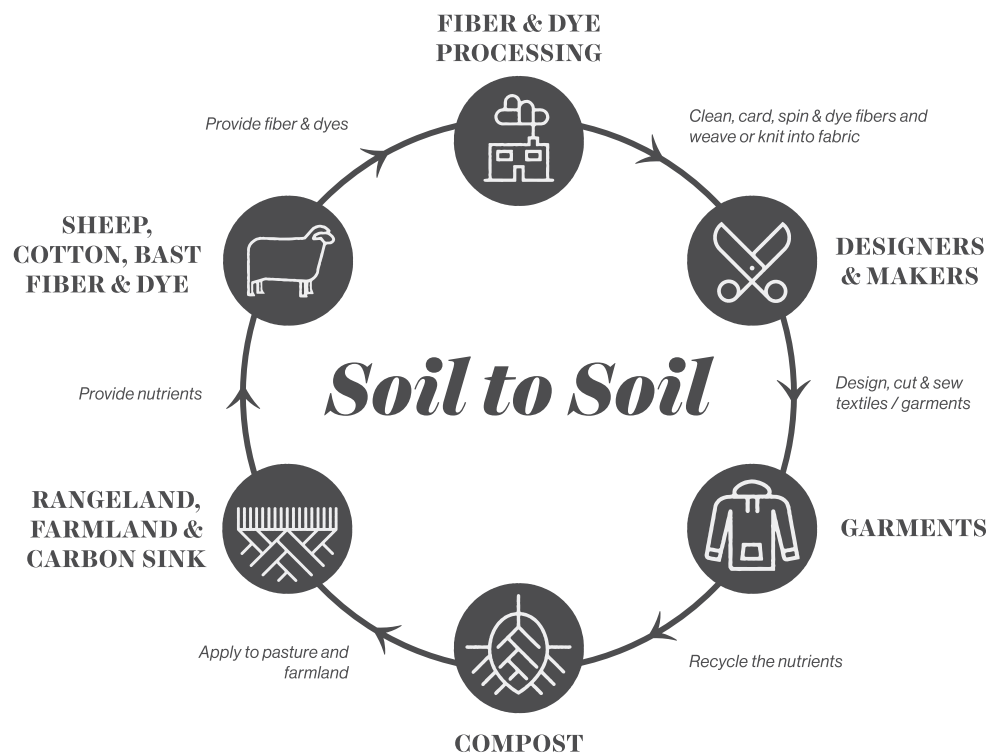
Introduction and Context

THIS STUDY was completed with funding generously provided by the Jena and Michael King Foundation, as part of Fibershed's True Blue project. Researching, engineering, and writing was led by Nicholas Wenner, with contributions from process engineer Matthew Forkin. The project aims to support a bio-regional manufacturing system for natural indigo-dyed textiles in the Northern California fibershed. It is one project of many that support Fibershed's larger mission:

“Fibershed develops regional and regenerative fiber systems on behalf of independent working producers, by expanding opportunities to implement carbon farming, forming catalytic foundations to rebuild regional manufacturing, and through connecting end-users to farms and ranches through public education.”

The present document represents a deep dive into one particular element of the indigo production system, concerning itself with the specific processes by which indigo is produced from plant sources and aiming to propose and implement a dye production system that balances technical, economic, environmental, and social goals. We believe filling out infrastructure in this particular process step provides the type of catalytic foundation that Fibershed aims for.

The ideal indigo dye system would be a closed-loop system that moves from soil to dye to textiles and back to soil. While each step is essential to the cycle, we chose to focus our efforts on the dye production step in this document 1) because it is lacking at large scale in our fibershed, 2) because it was the area of greatest unknowns, and 3) because



This document focuses on the dye processing step of the soil-to-soil textile cycle for natural indigo dye.

its manner of implementation has significant effects on the rest of the dye and textile system.

There are two main methods for dye production—compost and water extraction—and the choice between these methods greatly affects the rest of the production cycle. The compost method stems from Japanese traditions. It is a solid-state concentration process utilizing composting and resulting in a dyestuff that can be used in traditional Japanese fermented dye vats or in vats employing chemical reduction. The water extraction process draws mainly from sub-tropical traditions. It is a liquid-state process utilizing heat and/or fermentation and resulting in a concentrated powder of indigo pigment

that can also be used in both fermented dye vats and chemically reduced vats.

The first section of this paper compares the two processes in general and identifies the challenges and opportunities of each. The next section takes a detailed look at each process and gives recommendations for particular approaches to each. We then give results from quantitative modeling of each process, identifying and discussing key process parameters and expected inputs, outputs, and yields. In the following section, we propose specific designs for farm-scale indigo compost and water extraction dye systems. Finally, we present and discuss the results of economic modeling for each system and make recommendations for moving forward.

Comparing Dye Production Methods

WATER EXTRACTION AND COMPOST

IN THIS SECTION we compare the two predominant methods for the production of indigo dye from plants: the water extraction process and the compost process.

Overview

The water extraction process is a liquid-state extraction process that yields a powdered pigment with higher indigo purity than indigo compost. It involves extracting indigo precursors from freshly harvested plants by submerging them in a large tank. These precursors are hydrolyzed by heat and/or fermentation and subsequently alkalized and oxidized to produce insoluble indigo pigment, which precipitates and settles before being filtered and dried. Once dry, the pigment is compact, relatively homogeneous, predictable, and shelf-stable. See Appendix A for a diagram showing one version of the complete water extraction process.

The compost process uses composting to concentrate (rather than extract) indigo pigment from plants. In the Japanese tradition, plants are first harvested and dried. The leaves are then separated and composted for approximately 100 days, with frequent turning of the pile. After composting is complete, the remaining material (“sukumo”) is dried and bagged, ready for use in traditional dyeing vats. Indigo compost can also be produced using modern equipment and methods, and we explore this possibility in more detail later on.

The compost process is very attractive from cultural and environmental standpoints. One can see from the process flow diagram (Appendix B), that the process is much simpler than water extraction. It requires very little



Left, composted indigo (Photo by Paige Green) and right, powdered indigo pigment created with the water extraction process (Photo by Dustin Kahn)

in the way of water, and no chemical inputs are necessary. From growth to dye production to dyeing, the indigo compost method is a living process.

Artist and professional indigo dyer Rowland Ricketts trained in indigo growing and dyeing in Japan and practices the Japanese sukumo method in his work. He provides an excellent illustrated overview of the process on his website:

<http://www.rickettsindigo.com/#indigo>

It is the very living nature of the Japanese sukumo process that makes it challenging for application in scales beyond the artisan level. In fact, Ricketts argues that the process makes “absolutely no sense” for large-scale or commercial production. He chose the process for its history, and precisely because it is more difficult, unpredictable, and labor-intensive as a process than water extraction, and would be “almost impossible to commercialize,” suiting it to his work and message as an artist.

However, as concluded in the *Handbook of Natural Colorants*, the composting process “could repay a revisit.”

Mechanical crushing of the leaves, a controlled drying of the crushed material, more efficient couching [i.e. composting], and one has a reasonably efficient conversion to indigo in a process that has virtues of a lower energy input and almost no chemical inputs compared with the processes that involve steeping in water.”¹

In the following sections, we further compare the two processes and identify the challenges and opportunities of each. For the compost method, we describe the manual methods currently practiced in Northern California, which are based on the Japanese sukumo process, as well as new possibilities utilizing modern equipment.

Technical considerations

END PRODUCT

The output of the water extraction process is a powdered pigment that can serve as a direct substitute for synthetic indigo in the industrial dyeing process. This makes it much easier for a manufacturer to adopt ‘natural indigo’ into their existing process without needing to significantly change any equipment, processes, or products. Similarly, it would allow an emerging natural indigo manufacturer to take advantage of dyeing equipment developed for the synthetic indigo industry and already in existence.

¹ Bechtold, T ; Mussak, R (2009) “Handbook of Natural Colorants”

For both processes, the conversion of indigo precursors to indigo is not guaranteed, with alternative pathways creating impurities that can lower the indigo yield and even change elements of the color in dyed pieces. As discussed later on, the compost process appears to give higher yields of indigo than certain methods of water extraction, meaning that from a given acre of indigo plants more textiles could be dyed.

The chemical and biological complexity of the compost process may add complexity to the ultimate color achieved. Some feel that pieces dyed with compost have more complexity, depth, and beauty to their color, often citing the presence of the reddish indirubin pigment as a contributing factor. Los Angeles artist and dyer Niki Livingston, who dyes with Japanese sukumo, says as much. But—even for her—compost has its limitations when thinking about scales beyond the artisan level:

*“To be honest, sukumo might not be the way to go, as much as I hate to say it. It’s a superior product, but it’s not very accessible or easy.”*²

SCALE

The water extraction process can be carried with minimal modification from stove-top to industrial scale. The Japanese sukumo process is much more limited in scale, requiring both large minimum batch sizes and high labor content at all scales. The minimum size for one type of sukumo compost pile to retain heat and successfully decompose contains approximately 440 lbs of dried leaves.³

As artisan and indigo dyer Kori Hargreaves explains:

“Making a hot compost pile in the traditional Japanese fashion requires growing, harvesting, and drying around 5,000 indigo plants, which is not really possible

for those of us who grow indigo on a garden scale.

*I grow Persicaria tinctoria in three places: my home garden, my parent’s garden, and the garden where I work. Combined, this now amounts to between 200 and 500 plants, depending on the year. In order to gather enough leaves to make my own compost pile, I would need to harvest, dry, and store my indigo crop every year for the next several decades.”*⁴

Natural dye grower and instructor Dustin Kahn also prefers water extraction because she can complete the process at her small scale as a home grower. Not only that, she can do very small-scale dyeing with the concentrated pigment she produces from the water extraction. A sukumo vat, on the other hand, would require a much larger investment. For example, a typical naturally-fermented sukumo vat might be 60 gallons in size, requiring 22 lbs of sukumo and no less than a week of careful tending on startup.⁵

That’s not to say sukumo couldn’t be done on a large scale. Up until 100 years ago it was done at a huge scale in Japan, all by hand, with single compost piles weighing 5,000 lbs or more.⁶ Large-scale production in this way is indeed possible, but it would require large amounts of labor and attention, and likely cannot compete with water extraction in the modern market. Indeed, Ricketts suggests that the water extraction method “took over the world” and out-paced sukumo production precisely because

it produces a dyestuff that is purer, more concentrated, and easier to store and transport for far less cost.

While the water extraction process is indeed more flexible in scale than the Japanese sukumo process, more modern approaches to indigo composting greatly improve the process in this regard. For example, Fibershed’s recent experiments using industrial composting machinery to heat, stir, and aerate the material showed that successful composting is possible with less than 1 lb of dried leaves and with very little labor. We describe this process in more detail later on.

TIMING

The compost process currently employed in Northern California relies on drying the plants as quickly as possible after harvest, requiring large amounts of space and several days of reliable sunshine and dry weather. In our climate, with many areas receiving significant summer fog at night, this can be a significant challenge and could lead to major crop losses if no artificial drying methods are available.

The timing of the water extraction process depends primarily or only on catching the point of maximum indigo content in the plants. It is suitable for late harvests in our climate, when rains may make it difficult or impossible to dry plants outside in preparation for the compost process. In fact, Sonoma County indigo grower Craig Wilkinson used water extraction with his 2016 crop for that very reason. While Wilkinson at first intended to carry out the sukumo process, he was unable to harvest his plants before the weather turned, and rain and cold nights forced him to use the water extraction process instead.

² Personal communication

³ Personal communication with Rowland Ricketts

⁴ Hargreaves, K (2015) “Small-scale Indigo Processing” (<http://www.ecotonethreads.com/?p=247>)

⁵ Ricketts, R (2005) “Vatting and dyeing with Japanese indigo”

⁶ Personal communication with Rowland Ricketts

If the compost process employs drying machinery, however, the story is different. Leaves could be dried at any time. Unlike fresh leaves, dried leaves can be stored for later processing, meaning that the subsequent step of composting could be carried out at any point throughout the year. As we discuss later on, with industrial methods, composting could be completed in as little as one month and at any time.

PROCESS CONTROL

According to Ricketts, no one group in Japan is producing sukumo at a large scale, and all operations are carried out in the traditional way. He says the process has not been automated in large part because the country is aiming to maintain traditions. With indigo dyers designated as “living treasures,” the process must be done in the same way as it was centuries ago.⁷

Rowland’s process—which he learned through an intensive apprenticeship—has never been fully written down. For hundreds of years, he says, the knowledge of skilled sukumo producers was a carefully protected trade-secret held by a handful of competing clans that would punish anyone thought to be at risk of sharing their knowledge. This adds a certain mystique and allure to the process, but it also means that—at present—the process does not seem to be well understood scientifically or controlled with measurable process parameters. It is as much art as science, which presents significant challenges to larger-scale automated or semi-automated production, which require high levels of repeatability.

We are not aware of publicly available research on basic questions such as, “What is the ideal moisture content during composting?” In implementing or optimizing an industrial system, one would need to understand such basic questions to determine ideal conditions and process parameters.

Water extraction, on the other hand, has been well-documented and is much better understood at all scales. This is due—for better or worse—to the process of refining large-scale production facilities throughout the 17th, 18th, and 19th centuries in colonial indigo plantations across the world.

Greater control of process through water extraction may extend into the dyeing step, where the purer pigment from water extraction may reduce complications in both chemically and biologically-reduced dyeing, making pigment a more accessible dyestuff for many producers.

That being said, Fibershed’s recent experiments with industrial composting of indigo gave encouraging results, which are discussed later on, and reduction in dye vats with benign chemical reducers like fructose was shown to be viable at the artisan scale. While the efficacy of industrial-scale benign chemical reduction remains to be seen, improvements to the compost method in the composting and dyeing steps could give significantly more control than currently experienced.

Economic considerations

LABOR

When comparing sukumo with water extraction, Rowland Ricketts argues:

“The minute you start looking at it business-wise, it makes absolutely no sense to use the sukumo process. You won’t be able to compete.”

This is primarily a concern of labor. While the water extraction method does require significant labor from harvesting, fermenting, extracting, filtering, and drying the pigment, the sukumo method requires far more. The steps in sukumo include harvesting, drying the plants, separating the leaves,

and tending compost for approximately 3 months, let alone the tending in the dyeing step required by a naturally fermented dye vat.

This problem is compounded by the fact that the labor intensity of sukumo production does not necessarily decrease with scale in the way it does with water extraction. For example, a giant compost pile still needs to be tended for approximately 3 months, and it is just as hard to move as a large number of small compost piles.

Of course, mechanical innovation in the drying, leaf separation, and composting steps would greatly reduce the labor required for the composting method.

While both compost and pigment can be reduced most easily with chemical methods, the chemical reduction route does present its own challenges. It was the one taken by Los Angeles artist and dyer Jane Palmer at the production natural dye house she ran in Los Angeles for many years. Palmer focused her work on indigo as the most viable natural dye for large-scale production, and found many challenges. As Palmer noted, the apparel industry is operating on extremely low margins. Her method was to chemically reduce natural indigo powder using reducers like thiourea dioxide, and this represented a balance of economic necessity and environmental concerns. The dyeing work was both physically and intellectually demanding, and Palmer found it difficult to retain workers.⁸

MARKET SIZE

It was not within the scope of this project to carefully study the market size of either indigo compost or indigo pigment and so we do not have conclusive data to present. This is in fact a critical next step in the process of evaluating the best path forward. Given the technical challenges presented by compost dyeing, we do expect its market size to be lower than that for pigment, at least initially. For the sake of the economic modeling presented in the later sections of this report, we have

⁷ Personal communication

⁸ Personal communication

done a quick review of the market and present some reference points below.

The Northern California fibershed currently produces on the scale of about 150 of pounds of indigo compost per year and is able to sell all of it at a price of \$65 per pound. Demand from artisans and craftspeople in the immediate community is very high, and Fibershed's Rebecca Burgess estimates that it would be safe to assume this market would support volumes in the low thousands of pounds per year at that price point without a significant sales effort.⁹ We also heard from a number of other small-scale and artisan producers such as high-end shirt maker Michael Masterson and artisan Niki Livingston of L.A.'s Lookout & Wonderland that they strongly desire indigo compost and have struggled to obtain it from any source.¹⁰ For example, Niki has spent the past number of years carefully cultivating a relationship with a Japanese producer in the hope of buying some of his sukumo, but was disappointed to find out in 2016 that he had taken on a new apprentice and will have no spare compost to sell to her. Globally it appears that the majority of compost use is in a handful of traditional dye houses in Japan, with a growing niche artisanal market in the United States and beyond.

For pigment from water extraction, all Fibershed production is currently carried out on a garden scale, and we are not aware of any sales of pigment or price precedent. Instead we looked to larger producers and distributors around the United States and abroad. The most relevant reference point is Stony Creek Colors, a Tennessee-based

natural dye company that states on its website that their "goal for the next four to five years is to produce 15,000 acres of indigo in the USA. That means we can replace 2.8% of synthetic indigo dye globally." In 2017, Stony Creek worked with growers to grow a total of 160 acres of indigo¹¹, and they sell pigment listed at 40% purity for about \$90/lb directly to customers, perhaps with a lower price point for higher volume orders.

In terms of overall market size, natural indigo is said to account for approximately 1% of global indigo production, which can be extrapolated to be in the range of hundreds of tons per year.¹² It is generally available at 20-50% purity at a price range of \$20-\$70 per pound for low-volume buyers, depending on quality and source. We received a quote from one supplier from India at a price of \$16 per pound for large volumes.¹³ Much of the use is likely at artisan and small-to-medium industrial scales and production is concentrated in Asia, largely using the tropical indigo plant *Indigofera tinctoria*. The other ~99% of indigo used in the world today is produced synthetically from petroleum feedstocks, represents 3% of all dyes used globally¹⁴, and has a price around \$2.50/lb. Roughly 88,000 tons¹⁵ are produced each year with ~95% being used for the dyeing of denim for jeans.¹⁶

Plant-based indigo may never replace the current level of industrial synthetic production. There remains, however, ample room for natural indigo to grow for both artisan and small-to-medium scale industrial producers. A detailed study of the market sizes for compost and pigment at various price points

should be completed at a later time to support detailed business modeling. For the sake of the analysis in this report, we feel it is safe to assume ample demand for pigment from water extraction and more limited demand for compost.

Environmental and social considerations

From resource, waste, and cultural perspectives, the compost method is very attractive.

Ricketts comes to the sukumo process as an artist, and for his scale and purpose the process is "a natural fit." He notes that it works well with the climate and the seasons of his Indiana home. For example, in summer the dye vat is easy to maintain at ambient temperatures. The process requires no additional heat or chemical inputs and uses much lower quantities of water than the water extraction process, requiring only a space to compost the leaves and enough water to keep the compost going.

Ricketts argues that:

"[The water extraction system is] deeply rooted in colonialism and the caste-system. It's about people leaving the way of growing for themselves and their community and being forced to grow for the demands of a global industry. Think tobacco. Think sugar. Think corn." Sukumo, on the other hand, "forces you to a human scale."

⁹ Personal communication

¹⁰ Personal communication

¹¹ Henderson, N (2017) "How Stony Creek Colors Works with TN Farmers to Grow Indigo" (<https://www.tnhomeandfarm.com/agriculture/stony-creek-colors-works-tn-farmers-grow-indigo/>)

¹² Long, K (2008) "The Chemical Era" (<https://sites.google.com/site/kateannelong/thechemicalera>)

¹³ Personal communication with KMA Exports

¹⁴ Ghaly, A. et al. (2014) "Production, Characterization and Treatment of Textile Effluents: A Critical Review"

¹⁵ Franssen, M. et al. (2010) "Industrial Biotechnology in the Chemical and Pharmaceutical Industries"

¹⁶ ACS Chemical & Engineering News (2011) "Blue Jeans" (<https://pubs.acs.org/cen/science/89/8943sci3.html>)

He argues that truly sustainable solutions to the problems of the textile industry involve working at small regional scales.

“We are not going to solve our problems by making better denim with natural indigo and whatever else if we’re still producing billions and billions of pairs of jeans a year.”

The manual compost methods would certainly struggle to meet the demands of industry from the technical and economic considerations discussed above. To this, Ricketts would argue:

“I don’t want to meet the demands of industry. I think the demands of industry are our problem.”¹⁷

Dyeing with pigment from water extraction may be much more accessible to large-scale dyers, potentially leading to larger markets and impacts.

That being said, and recognizing that large-scale compost dyeing may present challenges that could limit market size and overall impact, modernizing the indigo compost process may overcome many of the limitations of manual methods, leading to clear and scalable social and environmental benefits.

Conclusions

The compost method as currently practiced in Northern California has many attractive qualities, but it is currently limited in scalability by issues of process timing, process control, and high labor content. It is therefore worth exploring possible tools and methods of reducing cost and increasing efficiency in a more automated process. There is clear demand for compost at small scale to supply artisans. At larger scales, ample markets may exist if compost dyeing methods can be easily scaled.

The water extraction method is more complex and in many cases has a larger environmental footprint, but has the potential to be easier to scale and to address a much larger market, and thus to have potentially greater positive impact. This motivates the exploration of methods to minimize negative environmental impact while designing a system at an appropriate scale of production.

Given these challenges and opportunities, we’ve taken our task to be three-fold:

1. Develop and model a scaled-up compost dye production system that leverages inherent environmental and social benefits while seeking to reduce labor and costs and to improve accessibility of the product.
2. Develop and model a scaled-up water extraction system that leverages inherent technical and economic advantages while addressing environmental and social goals.

3. Compare these two approaches and make recommendations for producers moving forward.

For both dye production methods, we chose to target a scale of up to 2.5 acres of planted indigo, which represents a good balance of practical and economic viability for individual farmers.

Indigo compost is the main process implemented by the northern California fibershed currently and it is well understood in that context. In the following section, we expand on current understanding and highlight possibilities for technical improvements. Later, we explore the details of the water extraction process and its variations and how it could be applied at scale within the Fibershed network. We then propose and compare designs for water extraction and compost systems at the farm-scale, giving economic analysis of both systems and making recommendations.



Separating dried indigo leaf from stems in preparation for the composting process at Fibershed’s 2016 demonstration farm (Photo by Paige Green)

¹⁷ All quotes from Rowland Ricketts in this section are from personal communications.

The Compost Method

IN THE FOLLOWING SECTION we present current processes for making and dyeing with indigo compost, identify the challenges of these approaches, and explore possibilities for addressing these challenges with modern equipment and techniques.

Current processes

WINNOWING, DRYING, AND COMPOSTING

Prof. Philip John offers an excellent overview of a modern Japanese sukumo process in his chapter in *The Handbook of Natural Colorants*. He uses the term “couching” as applied to the fermentation of European woad (*Isatis tinctoria*) to refer to the composting step undertaken with *Persicaria tinctoria* (syn. *Polygonum tinctorium*).

“The harvested *Polygonum* plants are chopped using a cutting machine and electric fans blow the leaves clear of

the heavier stem material. The leaves are dried for a day in the sun, then overnight in tobacco driers and set aside in straw bags until the autumn. It is not known whether these dried leaves contain indican or whether it has been converted to indigo at this stage. The next stage is equivalent to the couching process in *Isatis* processing. The dried *Polygonum* leaves are spread on the floor of a building dedicated to this stage of processing. The floor of the building is built up of successive layers of large stones, pebbles, sand, rice husks and clay. Both its structure and its sloping away from the centre act to draw water away from the composted leaves. Judicious sprinkling of water and a regular weekly (or more frequent) turning of the composting material facilitate the microbial activity that breaks down the leafy material. This causes the piles to shrink, allowing more material to be

added. The most important factor is the moisture content: too much will allow anaerobic pockets to develop and too little will prevent optimum microbial activity. Other critical factors are the turning of the piles to provide an even decomposition and an appropriate temperature of around 70°C. During the composting, any clumps that have formed are split up in a sieving machine. During the final period straw mats are placed on top and around the piles of decomposing leaves to insulate them against the lowest of the winter temperatures. Finally, the straw mats are removed, the piles are allowed to cool, excess moisture steams off and the sukumo is packed into straw bags. These will gradually lose further moisture and can be kept indefinitely. The couching lasts 100 days and results in an enormous reduction in the volume and a corresponding concentration of indigo.”¹⁸



*Above left, Japanese indigo producers using a wood chipper, fans, and brooms to winnow fresh indigo leaves from stems¹⁹
Above right, winnowed indigo leaves are laid out in a greenhouse and turned several times a day to dry.²⁰*

¹⁸ Bechtold, T ; Mussak, R (2009) “Handbook of Natural Colorants”

¹⁹ Image source: https://www.instagram.com/buaisou_i/

²⁰ Image source: https://www.instagram.com/buaisou_i/

The Northern California fibershed has practiced a similar method using a custom sukumo composting pad designed and built with the support of indigo dyer Rowland Ricketts. The process is effective, if labor intensive, and the resulting dyestuff has been used successfully in fermented dye vats stemming from the sukumo tradition. One challenge of this process is that the compost pile must be quite large to produce and maintain sufficient heat for efficient composting, requiring about 440 lbs of dry leaves.²¹ In northern California, the leaves are currently separated from the stems by drying the plants on tarps until the leaves are brittle and the stems remain supple. Stomping or otherwise crushing the leaves from the stems allows the stems to be manually lifted from the crushed leaf material. This process requires very large amounts of space for drying (up to 0.75 acres for every acre of indigo harvested, according to our measurements) and significant labor, and the process can be greatly affected by climatic variation and wind.

DYEING

Indigo must be chemically reduced in the dye vat to convert it into the water-soluble form useful for dyeing. This can be achieved through chemical or biological means. The compost dyeing method currently used in northern California is inspired by the Japanese sukumo process, in which the indigo is reduced via fermentation in a large vat. In this process, wood ash, limestone, and wheat germ are used to create conditions conducive to indigo-reducing microbial communities. The tending of this living system requires careful monitoring and experience. Starting it up can take more than a week, and it must be tended over time. Large amounts of compost are needed for a vat, which must be large enough to sustain the required conditions and typical small vats require as much as 22 lbs of compost to be successful.²²

²¹ Personal communication with Rowland Ricketts

²² Ricketts, R (2005) "Vatting and dyeing with Japanese indigo"



Drying indigo on tarps requires large amounts of space and leaves the drying process susceptible to climatic variation. (Photo by Dustin Kahn)



Above left, one method of separating leaves from stems takes advantage of the fact that the leaves can be dried to brittleness while the stems remain supple. (Photo by Paige Green).



Above right, Rebecca Burgess tending indigo leaf compost on a compost pad in Northern California that is based on the Japanese sukumo tradition and designed by indigo dyer Rowland Ricketts. (Photo by Dustin Kahn)

Possibilities for improved processes

In an effort to facilitate the process of indigo composting and increase the accessibility of the dyestuff, the True Blue project researched and experimented with various methods of automating or otherwise simplifying the processes of winnowing, drying, making, and dyeing with indigo compost. We present some of the major findings below.

WINNOWING AND DRYING

Some Japanese producers employ the method of chopping entire indigo plants when green then winnowing the resulting material to separate leaves from stems. Compared to drying on tarps, this significantly reduces the area needed for drying the plants. We propose facilitating the process further with one of the many machines used for leaf winnowing at industrial scales, such as those used for mint, tobacco, and parsley. We expect such machines to function well with *Persicaria tinctoria*, even if not originally intended for it. Specific machines are discussed later on.

Rather than drying winnowed leaves in large greenhouses, as practiced in by some Japanese producers, one could use one of a variety of drying methods used in industrial food production. For example, later in this report we discuss the use of rotary drum dryers from the tea industry.

COMPOSTING

The Japanese sukumo composting method is only one way to encourage the decomposition of indigo leaves and to form and concentrate the pigment within. The highly manual sukumo method developed over hundreds of years in Japan, and it may represent an ideal form for its context and its time. Taking this method as inspiration, our intent was to adapt the principles to our time and place, taking advantage of the tools available to us.



A fermented compost vat requires large amounts of compost and careful tending to be successful. (Photo by Paige Green)

Such tools include industrial composting machines, which facilitate the composting process by aerating, heating, and regularly turning composting material. Large machines can process multiple cubic yards of material at a time, and can do so in significantly less time and with less labor than manual methods. In order to prototype industrial composting for indigo, we acquired a small bench-top electric composter intended for kitchen food waste, the Compostio C30 Composter.

This machine can process several gallons of food waste per week, converting food scraps into usable compost in about two weeks. The composting chamber has a volume of about 0.5 cubic feet, and the machine automatically heats, aerates, and stirs the compost while maintaining moisture content and consistent temperature with its well-sealed and insulated design.



A tabletop composter (Compostio C30) used to compost indigo leaves²³

²³ Image source: <https://www.compostio.com/products/compostio-c30-composter>



Left: crushed, sifted, and rehydrated indigo leaves in a benchtop composter; center: the same leaves after 1 week of composting. The machine's rotating stirring bar can be seen in the second photo. Right: using industrial composting machines, indigo compost can be made in 3-4 weeks with minimal labor. (Photos by Nicholas Wenner)

With minor modification, the machine produced a high quality indigo compost dyestuff in 3 - 4 weeks. Compared to the 3-month duration and weekly labor of the sukumo method, this process required no labor other than loading and unloading the machine, and it allowed us to compost batches as small as 1 lb, compared to the 440 lbs required for the sukumo process.

With our experience at the tabletop scale, we believe that with proper tuning and process controls, an industrial composter could successfully process indigo leaves at a faster rate than traditional methods without reducing the yield.

Careful attention may need to be paid to the moisture content, temperature, aeration, density, and other key factors to deliver optimal results. Determining these key process parameters will require time and research, and we assume they can be determined and then implemented for reliable results.

DYEING

Motivated by the possibility of reducing indigo powder with benign chemical reducers like fructose rather than biological fermentation, the True Blue team explored the possibility of similar reduction and dyeing methods for indigo compost. In collaboration with



Cotton dyed with indigo compost that was produced by Craig Wilkinson (left) and others in Northern California. The dyeing was done using a fructose reduction recipe developed by Michel Garcia (right). (Photo by Dustin Kahn)

French natural dyer Michel Garcia, we adapted Garcia's fructose-reduction methods from indigo powder to compost, and found promising results.

The recipe involved soaking indigo compost in a large pot filled with hot water that had been run through hardwood ash. We then added fructose and calcium hydroxide and heated the vat to about 120 °F. Minutes later, the

dye vat was showing signs of reduction, and within 20 minutes we had dyed our first textile. According to Michel, the underlying function of the ash was to provide a source of potassium carbonate, which in combination with lime creates the strong base potassium hydroxide. This base serves partly to loosen the plant fibers and to help free indigo from the material. Michel suggested (and subsequent experience

verified) that preparing a vat in this way a day in advance of dyeing can increase dyeing performance as the compost fully hydrates and the process of reduction stabilizes. The recipe has not yet been optimized, but the approximate ratios used are instructive: 6 parts water, 3 parts compost, 3 parts wood ash, 1 part calcium hydroxide, to 1 part fructose (by mass).

While it is unclear how well the benign chemical reduction of compost scales in industrial production, working with Garcia proved for us that the process was possible, as well as viable and accessible at the home or artisan scale. The process requires far less time and experience than a fermented vat, and has the added advantage of flexible batch sizes. Whereas small fermentation vats require as much as

22 lbs of compost, we made successful fructose vats with less than 1 lb of compost.

The compost used in the experiments with Garcia came from a manual composting process. To verify the dyeing capabilities of the compost we produced using the tabletop composter, we carried out comparative dyeing tests. Equal weights of both types of compost were prepared in their own vats with equal ratios of water, wood ash, calcium hydroxide, and fructose. Once prepared the vats were allowed to sit and then heated to about 120 F. Equal weights of fabric were dyed in the same manner, and the resulting colors compared.

Based on the depth of shade produced, accelerated compost performed as well or better than sukumo-style compost.

The source indigo crops did come from different years and locations and therefore likely had differing indigo concentrations, and the dye results may not be comparable on a one-to-one basis. That being said, the tests showed that industrial composting can easily produce a viable indigo dyestuff that is quite similar to California sukumo and that the fructose method is quite effective for dyeing with that compost.

In later sections we describe designs for an indigo compost system that utilizes the improvements in winnowing, drying, composting, and dyeing we've proposed so far. Next, we give an in-depth exploration of the other major method for producing natural indigo dye, the water extraction method.



Wool, linen, and cotton textiles dyed in a fructose vat with indigo compost prepared in a tabletop composter (Dyeing and photo by Dustin Kahn)

The Water Extraction Method

Overview

THE WATER EXTRACTION PROCESS has been practiced in various forms for hundreds and even thousands of years throughout the world. The basic steps of water extraction include extraction, alkalization, oxidation, and filtration. In the extraction step, the plants are submerged in water then heated and/or fermented to pull the indigo precursors out of the plant cells and into solution. After extraction, the spent plant material is separated and set aside. The remaining liquid is first alkalinized then oxidized to convert indigo precursors into the pigment molecule indigotin (see sidebar below). The insoluble indigotin precipitates, settles, and is filtered, optionally washed, and finally dried to produce indigo powder.

In the following sections, we explore the process and consider each step in more detail.



Indigo powder produced by Kori Hargreaves
(Photo by Kori Hargreaves)

Much of the technical information presented here stems from the work of Prof. Philip John from the University of Reading, who researched indigo from woad (*Isatis tinctoria*) and Japanese indigo (*Persicaria tinctoria*) extensively in connection with the EU-funded Spindigo Project from 2001-2004. The project aimed to introduce indigo-producing crops to European agriculture, and Prof. John provides an

excellent overview of indigo production and reviews the results of the project and other research in his chapter in *The Handbook of Natural Colorants*.²⁴

Information presented below also comes from artist, plant biologist, and indigo dyer Kori Hargreaves, who presents an excellent overview of the water extraction process for the home dyer with step-by-step instructions on her website:

www.ecotonethreads.com/?p=247

Hargreaves was kind enough to consult with the True Blue team multiple times throughout our research, sharing her extensive experience with the water extraction process as well as her curiosity and keen understanding of the underlying processes. She has been growing for the last five years, using the process described in the link above for the last four years. She learned the

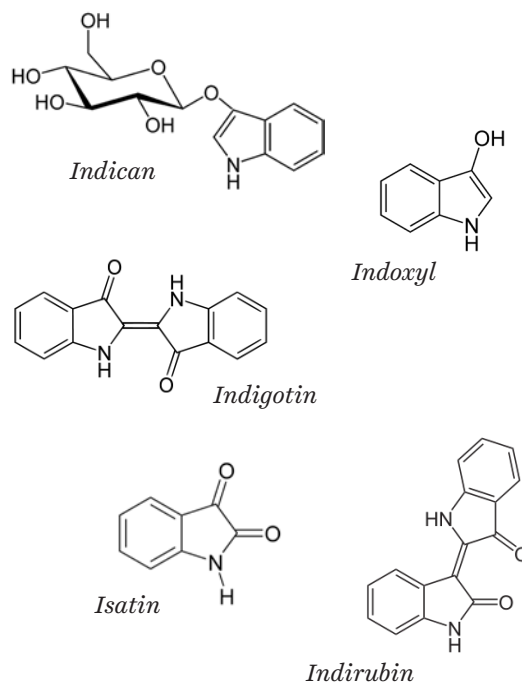
CHEMISTRY OF INDIGO EXTRACTION

The chemical precursor to indigo in plants is indican, a glycoside. It exists throughout the plant but is concentrated almost exclusively in the vacuoles of the leaves.²⁵ Although indican concentration can reach as much as a few percent of the wet weight of the leaves, we still do not fully understand its biological function for the plant.

The extraction and hydrolysis of indican (achieved through heat and/or fermentation in water) cleaves the indican into two parts, resulting in b-D-glucose and indoxyl. The hydrolysis is achieved via enzymes naturally present in the leaves as well as by the actions of microbes that likely seek the b-D-glucose as food.

The interaction of indoxyl with a mild oxidizing agent (such as atmospheric oxygen) under conditions of high pH yields the blue pigment indigotin (the active pigment in indigo dye).

Indigotin is only one of many oxidation products of indoxyl. Under non-ideal conditions, others—such as isatin and indirubin—can be formed, contributing to lower purity dyestuffs with lower quantities of the desired indigotin pigment.



²⁴ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

²⁵ Minami, Y. et al. (2000) "Tissue and Intracellular Localization of Indican and the Purification and Characterization of Indican Synthase from Indigo Plants"

water extraction process originally from Sarah Bellos, the founder of Stony Creek Colors, the only large-scale natural indigo dye producer in the United States.

Extraction

Harvested plants must be treated carefully before extraction, and leaf bruising is to be avoided. This is due to the fact that the plant leaves contain the enzyme needed to hydrolyze relatively stable indican into the unstable indigo precursor indoxyl. This enzyme, beta-glucosidase, is normally found in the chloroplasts of the leaves, whereas indican is found almost exclusively in the vacuoles.²⁶ Bruising the leaves risks bringing these two components together, causing premature formation and entrapment of indigotin inside leaf cells and/or the formation of non-indigotin oxidation products from indoxyl. This trapping of indigo inside the leaves is not an issue for the compost process, as trapped indigo is concentrated and freed later during the composting step. For the water extraction process, however, it is critical that indigo precursor molecules remain in the water-soluble indican or indoxyl form long enough to be pulled into the extraction liquid.

It can be helpful to thoroughly rinse the indigo plants prior to extraction to remove any soil particles that may be adhering to the plant. This serves two purposes. Firstly, compounds in the soil can react with indoxyl to form non-indigotin oxidation products, decreasing yield. Secondly, fine soil particles can be carried through the process and contaminate the final pigment product, reducing its purity.

This rinse step should be done with cold water and with short duration to minimize any chance of extraction occurring. One method is to submerge the plants in a cold water bath, agitate slightly, remove and drain. This can be accomplished manually in batches, or could utilize a continuous system with a belt carrying the plants through the bath and out to drain.

One study by Bechtold et. al (2002) on *Persicaria tinctoria* demonstrates that extraction should occur immediately after harvesting and certainly less than 1 day after harvesting.²⁷ In the study, researchers stored plants at approximately 20 °C for varying times before carrying out extraction, and drastic reductions in indigo content were observed even after a single day of plant storage. They also found that reduction in temperature may increase the allowable storage time.

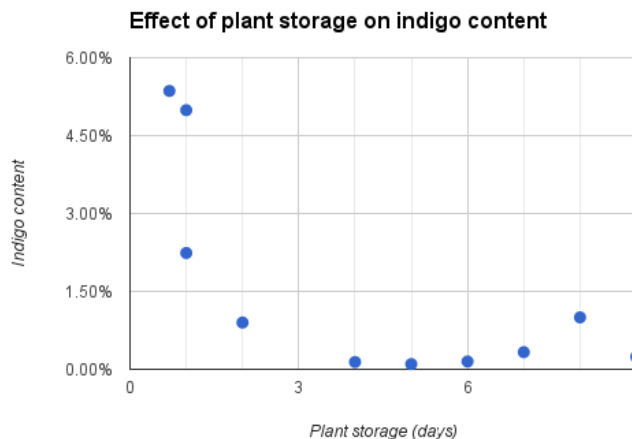
In the extraction itself, plant material is submerged to extract indican from the plant material and heated and/or

fermented to hydrolyze the indican and produce an indoxyl-bearing solution. Fermentation may also serve to lower the dissolved oxygen content in the extraction liquid, preventing premature and unintended oxidation of indoxyl. Excessive introduction of oxygen at any point can decrease pigment yields, and the plants should be completely submerged to limit exposure to oxygen. Similarly, the vat should be disturbed minimally throughout the process and the exposed liquid surface should be minimized to limit the introduction of atmospheric oxygen to the liquid.

Extraction can be carried out using fermentation over a period of days, with heated water over a period of hours, or with a hybrid method that uses warm water and requires less time than fermentation and more time than heated extraction.

FERMENTED EXTRACTION

The required time for fermentation varies with conditions, but with unheated water in temperate regions roughly 3-5 days may be expected, though some sources report times as short as 14 hours in tropical regions.²⁹ Indoxyl is unstable at this point, and timing and tending the extraction to obtain maximum yields and avoid undesired oxidation products is key.



*Indigo yields decrease drastically and quickly if harvested plants are stored before extraction.*²⁸

²⁶ Angelini, L. et al. (2005) "Extraction of indigo from *Isatis tinctoria* L. and *Polygonum tinctorium* Ait. as a basis for large-scale production"

²⁷ Bechtold, T. et al. (2002) "Process Balance and Product Quality in the Production of Natural Indigo From *Polygonum Tinctorium* Ait. Applying Low-Technology Methods"

²⁸ Bechtold, T. et al. (2002) "Process Balance and Product Quality in the Production of Natural Indigo From *Polygonum Tinctorium* Ait. Applying Low-Technology Methods"

²⁹ Personal communication with Kori Hargreaves

While it is not clear exactly what mechanisms are at play, indigotin yield drops very quickly with over-fermentation.³⁰ If one ends fermentation too early, indican will be incompletely extracted and initial indigo yields will be low, but the plant material could be re-fermented and the yields regained. If fermentation goes too far, however, yields drop quickly and irreversibly.³¹

Gauging when fermentation is complete is an intuitive process that requires significant first-hand experience to optimize and achieve consistent results. That being said, Hargreaves notes that with some guidance most people do succeed in creating pigment on the first try. Rather than focusing on the time elapsed, she notes that most reliable indicators for understanding when extraction is complete include visual and olfactory cues.³²

Visually, the liquid will take on a very pronounced neon blue-green color when fermentation is nearing completion. There may also be a small amount of bubbles and a metallic blue cast on the surface of the liquid.

At the same time, the vat takes on a somewhat fruity smell that—while it may contain some rank notes—is not particularly offensive. Once the fermentation begins to go too far, the color changes from the lively neon blue green to a duller army green, and the smell changes from fruity and bright to something increasingly rank. Additionally, leaves go from green to yellow and develop a slimy coating.

Developing further anecdotal indicators as well as repeatable and reliable quantitative indicators would be a valuable area of further research.



*The color of extraction water when fermentation is nearing completion
(Photo by Kori Hargreaves)*

It is important to achieve evenness of fermentation throughout the entire batch, and there is a trade-off between minimizing water use and over-compressing plants, which could retard fermentation in some areas and produce uneven extraction. Ideally, plants are compressed only enough to remain below the surface of the water. The ideal quantity of water to use is explored in later sections.

One might wonder if the plants can be macerated to speed up extraction time, to increase extraction amount, or to cut down on water use. One study on tropical indigo varieties reports that cutting raw material to small pieces can decrease unpleasant smell and ease the disposal of waste, but it is unclear what effect this has on indigo yield or purity.³³ Macerating the leaves and exposing them to oxygen may produce indigotin inside the plant cells before indican can exit the cells and enter solution in the

extraction, making the separation of pigment from leaves extremely difficult. Plant maceration could possibly occur underwater or in an otherwise low-oxygen environment, but it is unclear whether this is feasible or whether the effort would be justified. Additionally, maceration may lead to a lower purity in the final product due to particles of plant material contaminating the pigment.

HEATED EXTRACTION

Due to the difficulty in controlling or optimizing the state of fermentation, this process may be difficult to scale with reliably high yields. Fermentation can be aided with the addition of warm water or even supplanted by completing extraction in hot water. A hot water extraction is controlled by the temperature and the time of the extraction and the quality of the water, all process parameters that can easily be controlled and optimized for reliable results.

Indican breaks down quickly at temperatures around 185 °F and above, and thus any heated extraction must be carefully controlled to remain below this limit.³⁴ Furthermore, the enzyme from the leaves required to hydrolyze

³⁰ Personal communication with Kori Hargreaves

³¹ Personal communication with Kori Hargreaves

³² Personal communication with Kori Hargreaves

³³ Chanayath, N. et al. (2001) "Pigment Extraction Techniques from the Leaves of *Indigofera tinctoria* Linn. and *Baphicacanthus cusia* Brem. and Chemical Structure Analysis of Their Major Components"

³⁴ Personal communication with Kori Hargreaves

indican into indoxyl, beta-glucosidase, is denatured at elevated temperatures, being completely inhibited at 60 °C (140 °F).³⁵ At this temperature, the enzyme fails to act, little or no indican is hydrolyzed to produce indoxyl, and little or no indigo results.

Defining the ideal temperature and time to maximize the yield and efficiency of heated extraction was a key area of our research. Clearly, the temperature must be below 140 F, and the extraction time would ideally be as short as possible. Some sources recommend extraction times of 4 hours at 40 °C, or 24 hours at 25 °C.³⁶ Others carried out extractions at 50 °C for 30 minutes, or 25 °C for 72 hours.³⁷

In consultation with French natural dyer Michel Garcia, we arrived at a time/temperature for extraction that balances considerations of yield with practicality and efficiency of the process. Garcia has worked with indigo for decades, and he has designed and built many heated water extraction systems throughout the world. After 20 years of experimentation, Garcia recommends extraction at a constant temperature of 50°C (122 °F) for 2 hours. Above 56-57 °C, Garcia has experienced significant losses in yield. Soaking for longer than 2 hours creates excessive saponins, which cause foam and inhibit aeration in the subsequent processing.³⁸

HYBRID EXTRACTION

Hargreaves used heated water extraction in her first year with indigo while operating at a stove-top scale. At larger scale, she found the process to require too much energy and went to a hybrid method with solar-heated warm water going into the steeping tanks. She prefers the process to a straight fermentation because it allows for more complete and even extraction from all the plant material in the batch as well as speeding extraction. For her climate near the Santa Cruz mountains, she filled her tanks with 110°F water and left batches to soak for about 24 hrs. At 135°F, she recommends no more than 12 hrs.³⁹

The exact time needed for hybrid extraction at given starting temperature will depend on climate. In gauging the completion of extraction, one cannot rely on the same indicators used in fermentation. With warm or hot water, other compounds in addition to indican are pulled into solution, and the resulting color is not neon green, but a deeper chestnut brown. Similarly, the olfactory cues differ. Developing reliable indicators for hybrid extraction would be a valuable area for further research.

Using warm water or hot water in the extraction process is certainly attractive for improving process control and reliability and decreasing extraction time.

For the purpose of a garden-scale system, fermentation, heated, or hybrid approaches may all be acceptable.

For the purpose of a larger scale system, a fermentation approach requires long batch times on the order of days to a week, and thus would require many small tanks, or a few large tanks. This would require investment in a large installation in one place, something that may make sense in the future but that seems unlikely for the Northern California fibershed in the near future. Conversely, a heated extraction approach can have very short batch times on the order hours, and thus can be accomplished with a much smaller physical equipment footprint. A hybrid approach would lie somewhere between the two, requiring less energy but more space and time than heated extraction. Both hybrid and fermented approaches are susceptible to climatic variation (unless they are housed in a climate controlled space), and for this reason are harder to control and predict than the heated approach.

In this report, we pursue the heated extraction approach for reasons of process control, predictability, and reduced space and time requirements. We used Garcia's recommendations (50 °C for 2 hours) when carrying out key extraction experiments and when designing and modeling the water extraction system presented later in this report.

³⁵ Minami, Y. et al. (1996) "Purification and characterisation of a b-glucosidase from *Polygonum tinctorium*, which catalyses preferentially the hydrolysis of indican"

³⁶ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

³⁷ Angelini, L. et al. (2005) "Extraction of indigo from *Isatis tinctoria* L. and *Polygonum tinctorium* Ait. as a basis for large-scale production"

³⁸ Personal communication

³⁹ Personal communication

Alkalization

Alkaline pH accelerates the conversion of indoxyl to indigotin.⁴⁰ Hargreaves notes that indoxyl oxidation and indigotin formation at a pH of 3 is essentially non-existent and that conversion efficiency tops out at approximately pH 9.5 without dropping significantly at higher pH.⁴¹ Vuorema notes that a pH of 11 is the most suitable for indigo production when using calcium hydroxide as an alkali, when both quantity and purity are considered.⁴²

Indigo can be formed without alkalization, albeit more slowly and perhaps with lower conversion efficiency. For example, Jesus Ciriza Larraona, the founder of the Indian natural dye house The Colours of Nature, claims his indigo suppliers don't use any alkalis in their water extraction facilities (which use *Indigofera tinctoria*).⁴³

CHOICE OF ALKALI

The ideal pH can be achieved with the addition of many possible alkalinizing agents, with commonly used options including calcium hydroxide, ammonia, and sodium hydroxide.

A key consideration in choosing an alkalinizing agent relates to greywater treatment. Depending on the treatment method and the alkalinizing agent, more or less benign materials will be employed and produced. For example, when using ammonia as an alkalinizing

agent, greywater could be neutralized with sulphuric acid, producing ammonium sulphate, which is used as a non-organic crop fertilizer. Both ammonia and sulphuric acid, however, are quite noxious and potentially dangerous to produce and work with.

In later sections, we propose calcium hydroxide as an ideal alkali for the relatively benign nature of its manufacture, its low cost, its dual functions as an alkali and flocculant, the relatively benign nature of the greywater produced, and the opportunities it presents for simple and effective greywater treatment.

When using calcium hydroxide, Michel Garcia recommends first aerating the extraction liquid prior to adding the alkali. The intent is to increase the concentration of carbonic acid in the liquid, which derives from atmospheric carbon dioxide introduced during aeration. This carbonic acid will react with calcium hydroxide in the following steps to create calcium carbonate, the presence of which aids in the flocculation and settling of the indigo. This is done before the addition of alkali because indigo will begin to form and flocculate immediately upon alkalization, and excessive disturbance of this indigo can break the flocculate down into very fine sizes that are difficult to settle and filter.⁴⁴

Oxidation

Once alkalized, the indoxyl solution in the extraction vat is ready for conversion to indigotin. This oxidation step is achieved simply by exposing the liquid to atmospheric oxygen. This can be done in many ways, some taking more and some taking less time or effort. For example, large cement tanks used in India are aerated by a team of workers standing in the water and coordinating forceful kicks of their legs. This process reportedly takes about 2 hrs.⁴⁵

Bechtold notes that oxidation can occur with time alone, citing successful indigo formation over the course of 4-5 days with occasional stirring in open containers, albeit with low yields.⁴⁶

On the other end of the spectrum, one can bubble pressurized air (or even pure oxygen) through the extraction liquid to achieve rapid oxidation. Vuorema studied 5, 15, 45, and 60-minute aerations using pressurized air with *Isatis tinctoria*, finding 15-minute and even 5-minute durations to be sufficient.⁴⁷

One will know the oxidation process is going well if the extraction liquid and foam that forms at the surface turn distinctly indigo in color. The oxidation is complete when a sample of liquid that is allowed to settle yields a reddish brown liquid layer on top with a settled layer of indigo pigment at the bottom. By this point, foam may have stopped turning blue or disappeared.

⁴⁰ Cotson, S ; Holt, S (1958) "Kinetics of aerial oxidation of indoxyl and some of its halogen derivatives"

⁴¹ Personal communication

⁴² Vuorema, A (2008) "Reduction and Analysis Methods of Indigo"

⁴³ Personal communication

⁴⁴ Personal communication

⁴⁵ NGC Agro Industries "Indigo Dye Cake" (www.nccagroindustries.com/indigo-dye-cake.htm)

⁴⁶ Bechtold, T. et al. (2002) "Process Balance and Product Quality in the Production of Natural Indigo From *Polygonum Tinctorium* Ait. Applying Low-Technology Methods"

⁴⁷ Vuorema, A (2008) "Reduction and Analysis Methods of Indigo"

Filtration

Once formed, indigotin must be separated from the rest of the extraction liquid. On a relatively small scale, artisans like Hargreaves recommend a series of settling and decantation steps to concentrate the pigment into a slurry, then filtering with a fine cloth. Hargreaves recommends 8 mm habotai silk or even the finer 16 mm habotai silk as a filter cloth. After draining for 12-24 hrs, the slurry is ready for final drying and storing.⁴⁸

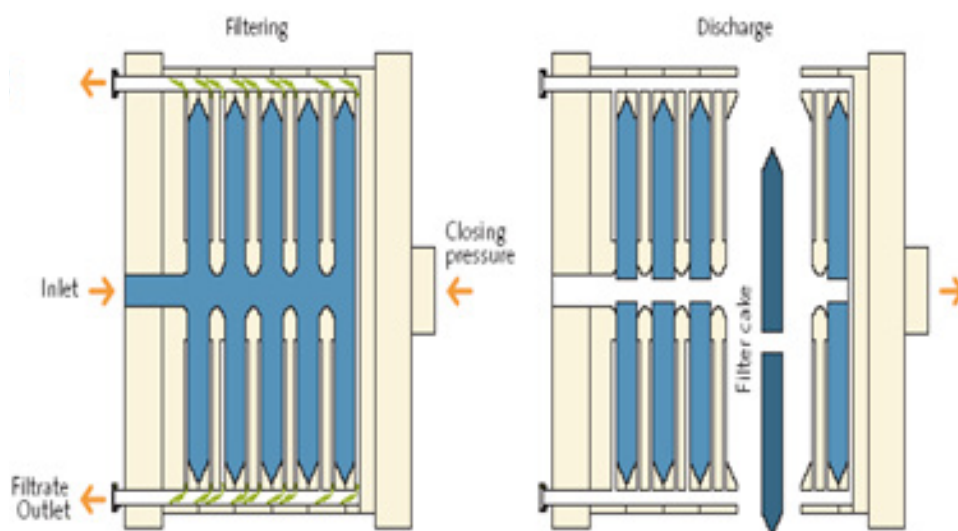
On a larger scale, more elaborate filtration systems may be desirable. One mature filtration technology that could serve our purposes is a filter press. Such equipment may even eliminate the need for flocculation, allowing for lower levels of chemical inputs. Other tools such as centrifugal concentration could be used in addition to or in place of filtration.

Michel Garcia recommends simpler approaches, opting to use decantation and conical fabric filters that employ only gravity and simple filtration. He argues that pressurized systems like a filter press can break apart flocculated indigo and send it through the filter. Fibershed's experiments showed that simple woven filters with mesh sizes of 25 microns served well for filtering large batches of indigo, although it took several days to produce a paste dry enough to collect and dry.

Prior to drying, the indigo slurry can be optionally washed to remove water soluble impurities (such as any previously undissolved calcium hydroxide) before final filtering and drying, ideally in acidic solution. For example, hydrochloric acid can be used to remove the calcium carbonate that forms from calcium hydroxide and aids



(Above) Indian workers oxidizing a tank of indigo⁴⁹
(Below) Diagram showing the operation of a filter press⁵⁰



⁴⁸ Personal communication

⁴⁹ Image source: http://www.industryofallnations.com/Jeans-At-Industry-Of-All-Nations-ccid_80.aspx

⁵⁰ Image source: http://ipoh.all.biz/filter-press-g14319#.WJkrShD8_g8

in flocculation, in one study improving pigment purities from an average of about 20% to 69%.⁵¹

While indigo could be left with residual water and stored as a paste for up to a year, full drying ensures the longest shelf-life and allows the pigment to be stored for indefinite periods. That being said, dyers like Michel Garcia argue that indigo paste is a more efficient dyestuff. Having never been fully dried, he argues it is easier to fully rehydrate and utilize in the dyebath.⁵²

Greywater

A large-scale water extraction system will result in large amounts of alkaline greywater containing significant amounts of organic material, and finding creative methods for treating and cycling greywater in regenerative or benign ways is a primary challenge of the water extraction process.

Indeed, rather than framing things in linear terms (“using and disposing of greywater”) we have an opportunity to think creatively about how we can responsibly and even beneficially cycle water and nutrients in our environment. One major path for such cycling is via application to agricultural lands.

Greywater could be treated in a way to render it relatively benign. For example, according to USDA soil scientist Ken Oster, we don’t have many problems with soil salinization in our area, so neutralization into various salts (e.g. calcium chloride from the neutralization of calcium hydroxide using hydrochloric acid) is a possibility. There are some soils closer to the Bay with salt problems, and salt application in those areas would not be desirable.

There may also be opportunities to use greywater as a resource for the amendment of soils or in the remediation of degraded soils. For

example, tomatoes benefit from nutrients like calcium that could be present in the alkalizing materials. In such cases, applying the greywater to cover crops might be good method for buffering over time. Similarly, applying greywater to more resilient crops (like hay) might be a desirable strategy (in contrast to application to tomatoes, which are quite sensitive).

In the case of acidified soils, remediation could be accomplished with untreated alkaline greywater. According to Oster, however, Northern California doesn’t have many acid soils. Soil acidification is primarily an issue in areas with high rainfall and excessive soil weathering, neither of which apply to the region. There are some small areas that would benefit from alkaline remediation: various soils in the delta with high organic material and especially acid sulphates, and soils near the mouth of the Napa River and the Bay near Novato.

Greywater could even be sold. From the varied agriculture of the Sacramento Valley, to dairy, oats, wheat, and silage in Marin County, and to dairies, vineyards, and pastures in Sonoma County, there could be many potential customers for irrigation water. For example, some of the dairies in the Laguna de Santa Rosa area in Sonoma County are irrigating pastures with purchased greywater. As mentioned earlier, the presence of ammonium sulphate (a commonly used fertilizer) as a byproduct of extraction with ammonia would likely be seen as a valuable asset to most non-organic farmers, potentially significantly increasing the price they would pay.

While there may certainly be possibilities for applying greywater to agricultural land, the strategy faces significant challenges: Not only must greywater suit the nutritional,

volumetric, and timing needs and application methods of the producers, it must also come at a low-price, and this is driven largely by the challenges of transportation.

If water is not cycled on-site, water transportation costs are a major issue for feasibility. According to our models, processing 1 acre of indigo via the water extraction process can produce as much as 32,000 gallons of greywater per acre per year. Given that water trucks commonly carry 4000-gallon tanks, this means a round-trip delivery would be needed for every 1.8- acre of indigo in production. These costs could add up very quickly, especially if recipients are not located close-by. A rough cost estimate for short transport distances is in the range of \$250 per truck load, and possibly higher if there is significant cost of disposal or processing of this water.

A much more cost-effective approach would be to dispose of greywater on-site, although repeated application of greywater to a single site could lead to environmental problems over time.

This highlights a central question:

How can we remove chemical additives from the water and cycle the two separately and—ideally—on-site?

In the next sections, we explore one possible solution to this question, highlighting calcium hydroxide as a promising alkalizing agent and outlining a simple and effective method of greywater treatment.

Calcium Hydroxide

The benefits of calcium hydroxide in the water extraction process lie in the relatively benign nature of its manufacture, in its low cost, in its dual functions as an alkalizer and flocculant, the relatively benign nature of the greywater produced, in the opportunities it presents for simple and effective greywater treatment and cycling.

⁵¹ John, P. et al. (2015) “The Production of Natural Indigo with a High Purity”

⁵² Personal communication

MANUFACTURE

Calcium hydroxide is typically produced through a relatively simple process involving 1) calcination of mined calcium carbonate (often limestone) and 2) hydration of the resulting calcium oxide (“quicklime”). In the calcination process, ground calcium carbonate is heated to approximately 1000 degrees C, where it breaks down into calcium oxide, a highly caustic and reactive chemical. Calcium oxide is “slaked” with the addition of liquid water, resulting in calcium hydroxide (“slaked lime”). Bulk calcium hydroxide is quite inexpensive, with prices on the order of \$80/ton.

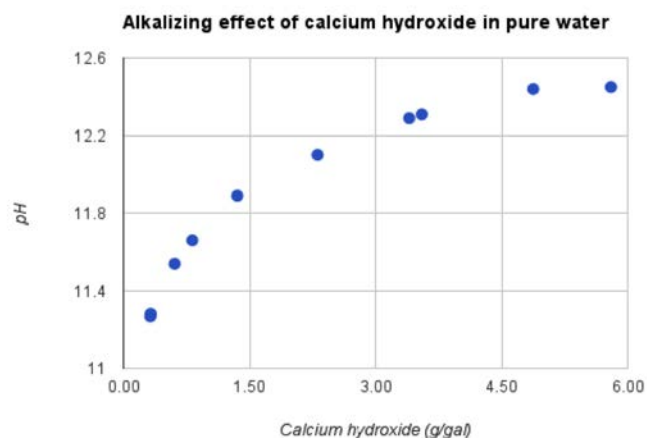
ALKALIZATION

Calcium hydroxide is an effective alkalizer, with only small amounts needed for indigo production. In Fibershed’s experiments with water extraction, less than 0.5 g of calcium hydroxide were required per gallon of extraction water to reach the target pH and achieve sufficient flocculation.

FLOCCULATION

Flocculation refers to any process by which small particles suspended in solution are caused to gather together into clumps (“flocs”), thereby facilitating sedimentation or filtration. Slaked lime is commonly used as a

flocculant in greywater treatment. The mechanism: “When lime is added to water the pH increases, resulting in the formation of carbonate ions from the natural alkalinity in the water. The increase in carbonate concentration together with calcium added in the lime results in the precipitation of calcium carbonate (CaCO_3). The calcium carbonate crystals enmesh colloidal particles.”⁵³ In indigo production, this enmeshment occurs between small, suspended indigotin particles in the extraction liquid and causes the pigment to clump together and settle quickly to the bottom. Without a flocculant, pigment could take weeks to settle.



*Only small amounts of calcium hydroxide are required to raise pH in pure water.*⁵⁴

⁵³ eWISA “Water Treatment Processes”

⁵⁴ National Lime Association “Lime: The Versatile Chemical” (www.lime.org/documents/lime_basics/lime-physical-chemical.pdf)

2 minutes... 10 minutes... and 30 minutes



When using baking soda as an alkalizer (right jar), Hargreaves found that settling can take weeks or even months. In contrast, using calcium hydroxide (left jar) can give settling times of less than 30 minutes. (Photos by Kori Hargreaves)

Flocculation is certainly helpful when settling pigment and decanting the remaining water to concentrate it. It may not be strictly necessary if filtration rather than sedimentation is used to isolate extracted pigment.

A significant amount of calcium hydroxide added to process water will convert to calcium carbonate and be associated and removed with the flocculated pigment. This removes alkaline compounds from greywater, but also decreases the purity of the resulting pigment.

GREYWATER TREATMENT

Calcium hydroxide can be neutralized by the application of various acids, including hydrochloric acid or citric acid, and the reaction products (calcium chloride and calcium citrate, respectively) are both relatively benign, being used even as soil amendments in special circumstances. For example, dry-farmed tomatoes need application of calcium regularly. Similarly, gypsum is often used to soften clayey soils, and calcium chloride would serve the same purpose.

But the real elegance of calcium hydroxide lies in the ability to achieve neutralization using ambient atmospheric carbon dioxide, and this yields a product that is not only benign or beneficial, but easily filterable and removed from the greywater itself. What is more, this process also serves to close the loop on the cycle from which calcium hydroxide derives in the first place.

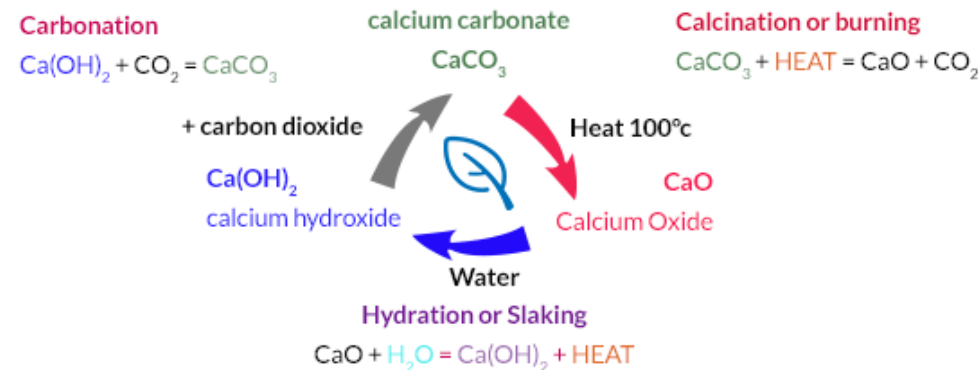
The lime cycle

Calcium hydroxide is produced from natural sources of calcium carbonate like limestone, which itself often derives from the calcium carbonate-rich skeletons of marine organisms. Calcium carbonate is the more stable material, and calcium hydroxide tends to convert back to that form, completing what is known as the lime cycle.

In industrial production of calcium hydroxide, the calcium carbonate feedstock first undergoes calcination, a process of heating to approximately 1000 degrees Celsius whereby calcium carbonate yields calcium oxide and carbon dioxide. This calcium oxide (quicklime) is highly caustic and unstable in the presence of moisture and CO₂. To produce calcium hydroxide (slaked lime), quicklime is exposed to water (“slaking”)—an exothermic reaction. If that calcium hydroxide is placed in water, it dissolves into calcium and hydroxide ions and the resulting solution is referred to as limewater. Once the limewater is exposed to carbon dioxide (even ambient carbon dioxide in the atmosphere), the dissolved calcium hydroxide reforms calcium carbonate, ending the cycle where it began.

Calcium carbonate precipitation

Associated amounts of calcium carbonate and calcium hydroxide have roughly equivalent effects on soil pH and



*The Lime Cycle*⁵⁵

carbon sequestration when contained in greywater. However, calcium carbonate has a particular and very helpful property that calcium hydroxide does not share: It has very low solubility in water, dissolving at only about 13 mg/L at neutral pH, compared to about 1700 mg/L for calcium hydroxide.⁵⁶ This means that if all calcium hydroxide used in the indigo process can be converted to calcium carbonate, about 95% percent of that calcium carbonate could be removable in the form of a precipitated solid. This precipitate could be filtered, removed, dried, and used or sold elsewhere as—for example—a soil amendment. It could even be sent back through the lime cycle (via recalcination and rehydration) and used again as calcium hydroxide, representing a nearly closed-loop system. Remaining greywater would contain only very small amounts of calcium carbonate (up to the limit of solubility).

In reality, 100% conversion of calcium hydroxide into calcium carbonate does not occur, as some proportion of the calcium ion will go to the formation of the highly soluble calcium bicarbonate, especially at low pH.⁵⁷ Is it not yet clear to the authors what the maximum conversion rate of calcium hydroxide to

precipitated calcium carbonate would be and what the process and conditions are to achieve it, but the information certainly exists. Precipitated calcium carbonate can be more pure and more highly controlled than that obtained from mined sources, and there is an industry of precipitated calcium carbonate (PCC) based on the neutralization of calcium hydroxide to calcium carbonate using carbon dioxide. According to one group, Specialty Minerals, the process is dictated by the control of reaction time, temperature, agitation, pressure, rate of carbon dioxide addition, and post-crystallization processing.⁵⁸

Our experiments show that passive neutralization is certainly possible, with 80-gallon batches of greywater dropping in pH from about 9.0 to neutral within 1 week when left open to the air.

With smaller batches of greywater, we observed and removed significant amounts of calcium carbonate and achieved neutral pH after exhaling through the liquid with a straw for about 1 minute.

⁵⁵ Image source: <http://www.singletonbirch.co.uk/lime/cycle>

⁵⁶ Wikipedia “Calcium Hydroxide” (https://en.wikipedia.org/wiki/Calcium_hydroxide)

⁵⁷ Wikipedia “Limewater” (<https://en.wikipedia.org/wiki/Limewater>)

⁵⁸ Specialty Minerals “What is PCC - Precipitated Calcium Carbonate?” ([http://www.mineralstech.com/Pages/SMI/Precipitated-Calcium-Carbonate-\(PCC\).aspx](http://www.mineralstech.com/Pages/SMI/Precipitated-Calcium-Carbonate-(PCC).aspx))

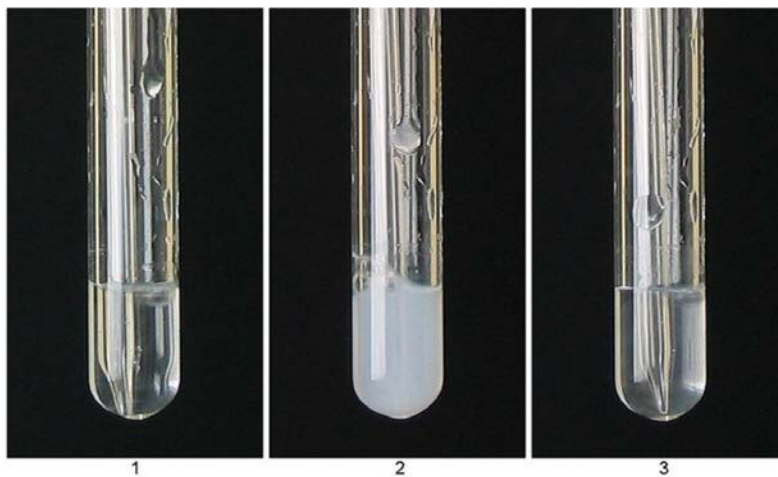
We believe the neutralization step could be greatly accelerated with agitation of the greywater and/or application of pure carbon dioxide. If optimized, we believe atmospheric neutralization represents an economical and sustainable solution for indigo greywater treatment.

Effects on soil

Both calcium hydroxide and calcium carbonate have applications in soil amendment or remediation, including in the sulphate soils mentioned previously and in many vineyards, which apply calcium or lime almost annually. Both materials are used as soil amendments to increase soil pH.

The molecular weights of calcium carbonate to calcium hydroxide are 1.35:1. For a given amount of slaked lime from indigo processing, one would end up with either (e.g.) 1 kg of slaked lime or 1.35 kg of calcium carbonate.

Associated amounts of calcium carbonate and calcium hydroxide have roughly equal effects on soil alkalinity upon dissolution in the soil. This is because the strongest effect on soil alkalinity comes from the shared calcium ion. There is a difference when the two molecules dissolve in soil: With calcium carbonate the calcium ion is accompanied by a bicarbonate ion and a hydroxide ion rather than two hydroxide ions as in the case of calcium hydroxide. This does affect neutralization of the active acidity, but not the (more important) potential acidity of the soil, and the result is that experts treat associated quantities of calcium carbonate and calcium hydroxide (1.35 to 1) as having equal effects on soil pH. For more detailed information about the processes and mechanisms in play, see “Lime



(images) Lime water (1), a dilute solution of calcium hydroxide, turns ‘milky’ when carbon dioxide is bubbled through it (2), forming a suspension of calcium carbonate. When more carbon dioxide is bubbled through it, the carbonate dissolves to form dilute solution of calcium bicarbonate (3). This reaction serves as a test for carbon dioxide.⁵⁹

Guidelines for Field Crops”⁶⁰ and “Liming to Improve Soil Quality in Acid Soils.”⁶¹

One might wonder if it is possible or desirable to apply greywater from dye extraction directly back onto the fields in which the indigo grew. While indigo does not require basic soil, the quantity of alkaline material used in the extraction process is quite low compared to that used in soil remediation. For example, in the case of calcium hydroxide, quantities in the range of 2,100 lbs/acre are used to raise pH by a single point.⁶² According to our models, if greywater from processing a single acre of indigo was applied directly back to the field in which that indigo grew, it would contain roughly 55 lbs of calcium hydroxide, or less than 3% of that typically used. If 95% of the calcium hydroxide is removed in the form of precipitated calcium carbonate (either with the flocculated pigment or in subsequent treatment), the alkalizing

potential of the greywater is truly negligible. Application of greywater directly back onto indigo fields (or any fields for that matter) is a distinct possibility on functional grounds.

Problematic is the fact that application of calcium hydroxide or calcium carbonate—even in extremely small quantities—may eliminate organic certification of the land in question.

Organic certification

Organic certification is meaningful to all the indigo growers Fibershed is working with at this time: Few currently own the land they tend, and all the landowners are certified and want to remain so.

If indigo farmers were to apply greywater from indigo production directly back into their indigo fields, and if the contents of the greywater compromise organic certification, landowners would have to wait until

⁵⁹ Image source: <http://mrtremblaycambridge.weebly.com/c11-preparing-common-salts.html>

⁶⁰ Foster, J. et al. (2010) “Lime Guidelines for Field Crops” (http://nmsp.cals.cornell.edu/NYOnFarmResearchPartnership/curriculum/Lime/Lime_UserManual.pdf)

⁶¹ USDA (1999) “Liming to Improve Soil Quality in Acid Soils” (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053252.pdf)

⁶² SFGate “Can I use Hydrated Lime to Raise of pH of Soil?” (<http://homeguides.sfgate.com/can-use-hydrated-lime-raise-ph-soil-98544.html>)

3 years after the last application for the land to again qualify for organic certification.

There are a few routes by which waste-products from calcium hydroxide could be used in agriculture. The use of the chemical in dye extraction could lead to at least four waste products: calcium carbonate (from carbonic acid neutralization), calcium chloride (from hydrochloric acid neutralization), calcium citrate (from citric acid neutralization), and calcium hydroxide (from non-neutralization). While all four are used as agricultural inputs to varying degrees, their use on organic-certified crops is very limited according to the Organic Materials Review Institute (OMRI). All three, however, are allowed as additives in organic food.

Calcium chloride is not generally acceptable as an amendment for certified organic crops, although it may be used only as a foliar spray to treat a physiological disorder associated with calcium uptake, and calcium citrate is not listed, meaning it likely is not permitted in any form.⁶³ The determinations for slaked lime and calcium carbonate are more nuanced, hinging on whether the materials are “synthetic” or “natural.” For either material to be considered natural, they must be mined directly from the earth and not produced by any other means.⁶⁴

In the case of calcium carbonate, natural sources are abundant. For example, calcium carbonate is a

common component in the bodies of marine organisms such as corals and molluscs and can be found abundantly in the mineral deposits that derive from them (such as chalk and limestone). Calcium carbonate can only be used as an organic soil amendment and crop fertilizer if it is mined from such sources.⁶⁵ On the other hand, synthetic calcium carbonate is commonly produced through the precipitation of (synthetic) calcium hydroxide, very much in the manner described above for greywater treatment. It is prohibited as a soil amendment, but it can be used as a livestock feed mineral.⁶⁶

Calcium hydroxide is generally produced through the calcination and rehydration of mined calcium carbonate (e.g. limestone). It is that calcination step that qualifies the substance as synthetic, being a change to the chemical composition of the substance at high temperatures. Synthetic calcium hydroxide is generally prohibited as a soil amendment, but it can be used in some applications for disease control.⁶⁷

Full conversion of calcium hydroxide to calcium carbonate could result in greater than 95% removal of the substance from dye extraction greywater, leaving only about 13 mg/L in solution. While such a small amount of remaining calcium carbonate seems negligible, it appears that the known presence at any concentration is significant enough to affect organic certification. This suggests the safest route would be to ensure that

any calcium carbonate in solution can qualify as “natural.” To understand how the source of calcium hydroxide would affect the determination of the resulting calcium carbonate, we consulted Jeffrey Stiles, the Marin County Inspector for the Dept. of Agriculture, Weights, and Measures:

“Starting with synthetic calcium hydroxide would cause the calcium carbonate produced to also be considered synthetic, and not allowed. My understanding is that if you sourced calcium hydroxide from a mined source there is a possibility that the resulting calcium carbonate could be considered non-synthetic (natural), and allowed.”⁶⁸

As Stiles notes, natural sources of calcium hydroxide are very rare. The name for the naturally-occurring mineral of calcium hydroxide is portlandite. One supplier, Excalibur Mineral Corporation, sells a limited supply of natural portlandite at prices close to \$600/lb, which would translate to about \$30,000 to process the indigo from a single acre. Staff at Excalibur doubt the mineral could be found at commercial quantities, let alone at reasonable prices.⁶⁹ Clearly, using natural sources of calcium hydroxide is not an option.

⁶³ Baker, B (2009) “Can I Use This Fertilizer on My Organic Farm?” (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_045863.pdf)

⁶⁴ Hollyer, J. et al. (2013) “The Allowed* Use of Commercial Fertilizers, Pesticides, and Synthetic Substances on U.S. Farms Under the USDA National Organic Program” (<https://www.ctahr.hawaii.edu/oc/freepubs/pdf/FST-56.pdf>)

⁶⁵ Hollyer, J. et al. (2013) “The Allowed* Use of Commercial Fertilizers, Pesticides, and Synthetic Substances on U.S. Farms Under the USDA National Organic Program” (<https://www.ctahr.hawaii.edu/oc/freepubs/pdf/FST-56.pdf>)

⁶⁶ OMRI (2016) “Calcium carbonate - feed mineral” (<https://www.omri.org/>)

⁶⁷ National Organic Standards Board Technical Advisory Panel Review (2002) “Calcium Hydroxide” (<https://www.ams.usda.gov/sites/default/files/media/Calcium%20Oxide%20TR.pdf>)

⁶⁸ Personal communication

⁶⁹ Personal communication

It appears that application of indigo greywater containing any amounts of synthetic calcium hydroxide or calcium carbonate to organic-certified agricultural lands is not a possibility.

According to the most recent Global Organic Textile Standard (GOTS), natural indigo dye and textiles produced with it can qualify as organic even if the crops used to produce the dye do not qualify as organic under OMRI.⁷⁰ It has not yet been determined whether the use of synthetic calcium hydroxide in dye extraction would maintain organic certification of dyes and textiles under GOTS. It is notable that Stony Creek Colors claims only that their dye is “natural” and does not use the word “organic” on their website.

Water Extraction Summary and Recommendations

For a method of large-scale indigo production using the water extraction method and that best balances technical, economic, environmental, and social goals, we have recommended the heated water extraction approach using calcium hydroxide as an alkalizer and carrying out greywater treatment with atmospheric carbon dioxide neutralization. This production process is a highly closed-loop process, potentially closing water, nutrient, and lime cycles on-site and producing minimum negative externalities.

Calcium hydroxide is the most promising candidate as an alkalizer in the dye extraction process due to the relatively benign method of its manufacture, its low cost, its dual functions as an alkalizer and

flocculant, the relatively benign nature of the greywater produced, and the opportunities it presents for simple and effective greywater treatment and cycling.

Untreated greywater with calcium hydroxide as an alkalizer would contain only small amounts of calcium hydroxide compared to the amounts used in soil remediation, and indigo greywater could be applied directly to agricultural lands with little ill effect. What is more, if indigo greywater is treated to convert calcium hydroxide to insoluble calcium carbonate and remove the resulting precipitate, any negative effects of the greywater on soil over time would be negligible. That being said, due to the classification of both the calcium hydroxide and calcium carbonate involved as synthetic compounds, greywater likely could not be applied to land while maintaining organic certification.



An image of the surface of the extraction liquid during a fermented water extraction process (Photo by Dustin Kahn)

⁷⁰ GOTS (2017) “GOTS Latest Version 5.0” (<http://www.global-standard.org/the-standard/latest-version.html>)

Process Modeling

IN ORDER TO QUANTIFY the compost and water extraction methods given the research presented above, we produced spreadsheet models of both the water extraction and the compost processes. Here we present the key parameters in the models and the expected inputs, outputs, and yields of each.

The models we introduce below also include economic modeling that is based on specific system designs we describe in the next section. The results of our economic models are reported in a later section

If you are interested in accessing these models, please contact us at office@fibershed.com.

Water Extraction Process Model

In this section we present and discuss the key parameters and results of the water extraction model.

KEY PARAMETERS

Through literature research and first-hand experimentation over two growing seasons, we identified and defined key parameters for the water extraction process. We explore a subset of the most fundamental parameters below.

Plant material

Values for planting density, plant weight, and plant volume come from Fibershed's field trials during the 2016 and 2017 growing seasons. In these trials, the field was laid in rows with 40" spacing and two plants were planted adjacently every 9" within each row. The value of the plant weight parameter represents a weighted average of plants harvested throughout the 2017 growing season. The volume parameter affects the size of the extraction system needed for a given weight of plant material, and its value

Summary of Key Parameters

Plant Material		
Planting density	34,165	plants/acre
Weight of plant material	0.63	lbs/plant
Volume of plant material	0.18	gallons/lb
Harvests per year	2	harvests
Extraction		
Extraction water	0.75	gal/lb plant material
Calcium hydroxide	0.75	g/gal extraction water
Yield		
Pigment (100% purity)	0.06%	of fresh plant weight

was determined from measurements in the 2016 growing season.

There is an opportunity to optimize indigo yield by varying the number and timing of harvests. We currently recommend 2 harvests per year. For more information, see Fibershed's separate report on indigo planting and harvesting.

These values give measurements from first-hand experience but may not be optimized. The value of each parameter will depend on conditions of time and place, and this will affect the size of the extraction system needed and the ultimate yield of pigment for a given acre of production.

Extraction

Understanding the minimum amount of extraction water needed for the dye extraction process is a key component of minimizing resource requirements and greywater production. Using more water than needed will increase calcium hydroxide requirements in proportion, as more of the chemical will be needed to reach the target pH. Using too little water can result in over-compaction of

the plant material, resulting in uneven and incomplete extraction. Our goal was to find the balance between the two constraints.

In our experiments we used progressively less water to search for the minimum necessary quantity. In one experiment, we used as little as 0.4 gallons/lb plant material. It may be possible to push this value lower, but qualitatively we judged the limit had been nearly reached and that further reduction of water would result in over-compression of plant material. We suggest 0.75 gallons/lb as a conservative target.

Minimizing calcium hydroxide requirements both increases purity of the final product and eases greywater treatment. The lower limit is defined by the need to both reach the target pH (approximately 10 or above) and to achieve sufficient flocculation.

The theoretical limit of solubility of calcium hydroxide in water at 20 degrees C is about 6.5 g/gallon and results in a pH of approximately 12.6. Even as low as .32 g of slaked lime per gallon pure water results in a pH of about 11.3.⁷¹ This suggests that

⁷¹ National Lime Association "Lime: The Versatile Chemical" (www.lime.org/documents/lime_basics/lime-physical-chemical.pdf)



In True Blue's trials, approximately 90 lbs of plant material was processed in 100-gallon tanks, producing pigment of 22% purity at a pure indigo yield of 0.06% of fresh plant weight. (Photos by Nicholas Wenner)

flocculation will define the lower bound of calcium hydroxide use rather than pH, and this was indeed our finding in practice.

When calcium hydroxide was applied in the form of limewater, we found as little as 0.5 g/gallon of extraction liquid to be sufficient for both pH and flocculation. We recommend 0.75 g/gal as a conservative target. Since the effects of calcium hydroxide on pH and flocculation may vary with each individual batch, in actual practice we recommend determining the ideal quantity by adding increasing amounts of calcium hydroxide to a test batch until the ideal conditions are reached.

Yield

The yield of pure indigo per acre has large consequences for any dye extraction system, including the economic viability of that system. Making reliable assumptions on indigo yield and purity is challenging: According to Prof. Philip John of the University of Reading, there is no consensus on generally accepted

methods for determining the purity of crude indigo pigment produced from plants.⁷² That being said, there are a number of methods currently employed, including spectrophotometric, electrochemical and standard dyeing approaches.

The value shown in the table below corresponds to the maximum yield we achieved. The value represents an average of two extractions carried out in 2017. These were carried out in

100-gallon tanks with extraction at 50 °C (122 °F) for 2 hours. The purity of the crude indigo produced was determined using spectrophotometric methods and dissolution in dimethyl sulfoxide in collaboration with the Dueber Lab at the University of California, Berkeley.

RESULTS

Based on the parameters above, we report the inputs, outputs, and expected yield from the water extraction process below.

Results (per acre per year)

Inputs		
Plant material	43,048	lbs
Irrigation water	448,412	gallons
Extraction water	32,286	gallons
Calcium hydroxide	53	lbs
Outputs		
Spent plant material	43,048	lbs
Greywater	32,286	gallons
Calcium carbonate (in solution)	3.5	lbs
Calcium carbonate (precipitated)	68	lbs
Yield		
Pigment (40% purity)	66	lbs
Pigment (100% purity)	27	lbs

⁷² Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

DISCUSSION

The most significant factors affecting yield and economic viability are the yield of plant material per acre and the yield of indigo from that plant material.

In Fibershed's 2017 trials in Northern California, *Persicaria tinctoria* was harvested twice and gave yields of about 43,000 lbs of fresh plant material per acre. For comparison, trials in central Italy gave yields up to 104,000 lbs per acre from two harvests.⁷³ Due to a wet spring and limited access to equipment, the California crop was not transplanted until late May, which was about 40 days later than might be expected. With earlier transplanting and well-timed harvests, we might expect significantly increased yields from California crops, which would translate into correspondingly increased yields of indigo per acre.

*The Handbook of Natural Colorants*⁷⁴ includes a literature review of the indigo content of various plant sources. It reports the fresh-leaf indigo precursor content in *Persicaria tinctoria* from five separate studies, giving an average indigo equivalent yield of 0.57% and ranging from 0.13% to 1.24%. These values refer only to the indigo content of the plant leaves, where indigo is most highly concentrated. The stems of the plant have much lower indigo contents, and their inclusion in the water extraction process we describe suggests lower maximum yields than these values. Assuming a 43% conversion of plant weight to leaf weight

Dye Production Method	Percent of max	Pure indigo yield from fresh plants	
		Min	Max
Theoretical Maximum	100%	0.04%	0.45%
Heated Water Extraction (True Blue)	13%	0.06%	0.06%
Heated Water Extraction (Spindigo)	12%	0.00%	0.06%
Optimized Water Extraction	56%	0.25%	0.25%
Fermented Water Extraction	77%	0.22%	0.35%

(as measured in our field trials), we might expect maximum indigo yields of 0.04% to 0.53%. The conversion of indoxyl to indigo, however, is always less than 100%.⁷⁵ One study focusing on indigo formation from indoxyl from the hydrolysis of indoxyl acetate by alkali in methanol showed a conversion rate of about 85%.⁷⁶ Assuming this conversion rate, we might expect the maximum possible yields shown in the table above.

The yields reached in Fibershed's 2017 experiments correspond well to those achieved by the EU-funded Spindigo Project. As part of this project, a mobile heated water extraction system was developed for *Isatis tinctoria*. When applied to *Persicaria tinctoria* in central Italy with extraction at 50 °C (122 °F) for 30 minutes, the system gave yields as reported in the table above.⁷⁷ Based on this research, *The Handbook of Natural Colorants* suggests pure indigo yields of about 46 lbs/acre⁷⁸, which corresponds reasonably well to the value reported above.

Some studies have attempted to increase indigo yield with the addition of commercial enzymes. For example one study, which extracted indigo from *Persicaria tinctoria* in acetic acid, acetone, and methanol and involved the addition of commercial beta-glucosidase, gave yields shown in the table above under "Optimized Water Extraction."⁷⁹

Vuorema provides a helpful overview of the considerations in the purity of crude indigo pigment produced from plant sources.

"Natural indigo contains, besides indigo, impurities such as indirubin, indigo-brown, indigo gluten and mineral matter. The indigo purity has been reported to be for woad indigo 20-40%, for P. tinctorium up to 12%⁸⁰ and for Indigofera indigo the highest, from 50 up to 77%."⁸¹

⁷³ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

⁷⁴ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

⁷⁵ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

⁷⁶ Russell, G ; Kaupp, G (1969) "Oxidation of indoxyl to indigo in basic solution"

⁷⁷ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

⁷⁸ Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

⁷⁹ Maugard, T. et al. (2002) "b-Glucosidase-catalysed hydrolysis of indican from leaves of *Polygonum tinctorium*"

⁸⁰ Bechtold, T. et al. (2002) "Process Balance and Product Quality in the Production of Natural Indigo From *Polygonum Tinctorium* Ait. Applying Low-Technology Methods"

⁸¹ Vuorema, A (2008) "Reduction and Analysis Methods of Indigo"

Other sources suggest different purities for indigo powder. For example, the purity of natural indigo powder from *Persicaria tinctoria* sold by Stony Creek Colors is advertised as approximately 40%, and purities claimed by other producers can range from about 20% to 50%. French natural dyer Michel Garcia argues that the maximum purity of indigo powder from *Persicaria tinctoria* is about 50%, due primarily to impurities resulting from the waxy cuticle of the leaves.⁸²

The low purity (22%) measured for True Blue's pigments from 2017 came as a surprise, given the visual similarities to pigment produced by Tennessee's Stony Creek Colors, which is advertised at about 40% purity. The two pigments were tested side-by-side, however, and the results are hard to deny. One explanation is that impurities may be coated by indigo molecules, giving a deceptively deep shade of blue to the powdered pigment.

Given the large effects purity and yield have on the economic viability of the water extraction process, it is important to validate the results of these tests. For now, given the similarity between yields from the True Blue and Spindigo projects, we believe the yields presented above represent reliable estimates for a heated extraction process, and we have used these values in our models.

It is possible that fermented extraction would give higher yields. Data is scarce, but one Korean study reported significantly higher yields than any of the methods discussed so far, and these are shown in the table on page 29.⁸³ With these higher yields, it may be that a fermented extraction system would give better economic results. Given the technical challenges of process control and the need for large investment and



Indigo samples produced by Stony Creek Colors (back, reported at 40% purity) and True Blue (front two, measured at average of 22% purity) (Photo by Nicholas Wenner)

a permanently installed system, we did not explore the fermented water extraction approach in detail in our research.

As mentioned above, it is possible that pigment yields could be greatly improved by increasing the yield of plant material per acre. In our economic modeling, we err on the side of caution, using only values for plant yield, pigment yield, and pigment purity that we have actually achieved.

One vendor of natural dyes in Northern California recommends using about

0.13 lbs of natural indigo dye for 1 lb of cotton.⁸⁴ According to Ryan Huston, the owner of Huston Textile Company in Northern California, a partner dyehouse used about 0.09 lbs of natural indigo per pound of cotton to complete a recent round of dyeing.⁸⁵ Averaging these values gives 0.11 lbs of indigo per pound of cotton. Assuming this utilization rate and 40% purity for pigment used, the pigment produced by the system we've modeled could dye approximately 630 lbs of cotton (or about 450 pairs of jeans) per acre.

⁸² Personal communication

⁸³ Shin, Y. et al. (2012) "Process Balance of Natural Indigo Production based on Traditional Niram Method"

⁸⁴ Dharma Trading Company "Natural Dyes (from plants and insects)" (<https://www.dharmatrading.com/dyes/natural-dyes-from-plants-and-insects.html>)

⁸⁵ Personal communication

Compost Process Model

This model uses the same assumptions and parameters as the water extraction model discussed in the previous section and includes additional values for the yield and purity of the indigo compost.

KEY PARAMETERS

Fibershed's field trials give estimates for dry leaf yield at 8.1% of fresh plant weight. Professional indigo dyer Rowland Ricketts, who makes and works with Japanese sukumo, estimates compost yield at 75% of dry leaf weight.⁸⁶

Combining these two values gives a compost yield of 6.1% of fresh plant weight.

The indigo purity of compost likely varies considerably, and little quantitative data was found to estimate it. One study measured the indigo purity of sukumo to be 3.2%, and we use this estimate in our model.⁸⁷

RESULTS

The inputs, outputs, and expected yield from the sukumo process are reported below.

DISCUSSION

Data on pure indigo yield from the composting process is limited. One source reports yields of about 20-50 g of pure indigo per kilogram of dry leaf.⁸⁸ The True Blue project measured a conversion of fresh leaves to dry leaves of 20% and a conversion of fresh plant material to fresh leaves of 43%. Applying these conversion factors gives pure indigo yields from compost of 0.17% - 0.43% of fresh plant weight, which is as high as 95% of the theoretical maximum yield presented in the previous section.

According to Rowland Ricketts, about 1.2 lbs of compost are needed to dye 1 lb of cotton.⁸⁹ Given this, the compost produced by the system we've modeled could dye approximately 2200 lbs of cotton (or about 1500 pairs of jeans) per acre. This is about 3.5 times the dyeing capacity per acre of the water extraction process discussed above.

Results (per acre per year)

Inputs		
Plant material	43,048	lbs
Irrigation water	448,412	gallons
Outputs		
Spent plant material (stems)	24,537	lbs
Yield		
Compost (3.2% purity)	2,615	lbs
Pure indigo	84	lbs

⁸⁶ Personal communication

⁸⁷ Miyoko, K (2009) "Characteristics of Color Produced by Awa Natural Indigo and Synthetic Indigo"

⁸⁸ Cardon, D (2007) "Natural Dyes: Sources, Tradition, Technology and Science"

⁸⁹ Personal communication

System Designs

IN THIS SECTION, we describe designs for both compost and water extraction systems based on the research and modeling we outlined in the previous sections.

Both systems are designed for a maximum capacity of 2.5 acres, which provided a good balance of technical and economic feasibility for individual farmers.

In the following section, we present and discuss the results of profitability modeling for these systems.

Water Extraction System

In this section we propose a detailed design for a semi-automated heated water extraction system. This design is used in the economic analysis presented in the next section.

SYSTEM DESIGN AND OPERATION

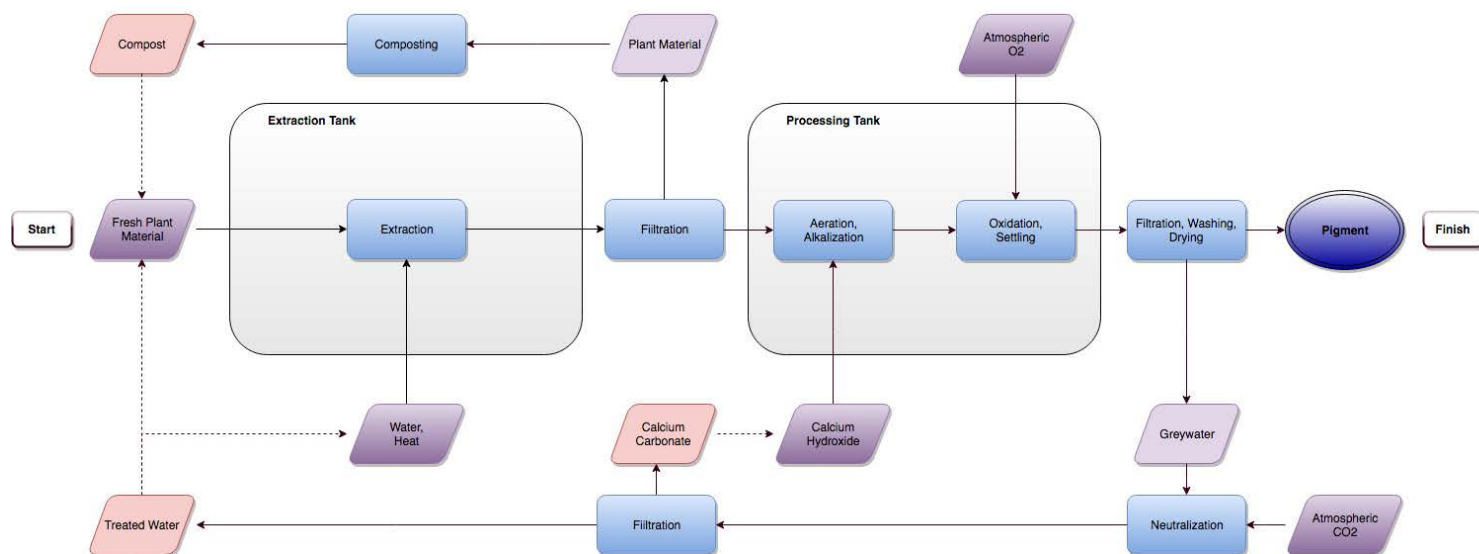
Multiple iterations for a heated water extraction system were considered, including a mobile shipping container-based system. It was found that a mobile system was impractical given small batch sizes and high labor content, and

a non-permanent system with large but movable tanks was devised.

The basic process is to 1) load fresh plants into a large extraction tank, 2) extract indigo precursors by steeping the material in heated water, 3) filter the extraction liquid into a second processing tank, 4) aerate and alkalize the liquid to create conditions conducive to indigo formation, 5) oxidize the liquid to form indigo, and finally 6) filter, optionally wash, and dry the finished pigment. A review of the key process steps and pieces of equipment follows.

Water Extraction Process

Dotted arrows indicate opportunities for semi-closed or closed-loop cycling. (Diagram by N. Wenner)



Extraction

While extraction could be carried out in large permanent tanks, we recommend carrying out this step in multiple batches in a single 5,000-gallon tank. This allows for less expense, greater mobility, greater modularity, and greater ease of handling. One 5,000-gallon tank could process plant material from about 0.25 acres per batch. Assuming 10 days of operation per harvest and 1 day of operation per batch, such a system could serve 2.5 acres of indigo in 20 days of operation over 2 harvest periods. After extraction, later processing steps would occur in a second 5,000-gallon tank.



We recommend the use of one 5,000-gallon tank for extraction and another 5,000-gallon tank for aeration, oxidation, and pigment formation.⁹⁰

To load and unload plant material from the extraction tank, we recommend building a custom metal crate to contain plant material that is lifted with a jib crane and hoist.



A jib crane⁹¹ and a manual hoist⁹² for lifting a custom crate for plant material in and out of the extraction tank

As discussed earlier, we explore heated water extraction in this report for the advantages it brings in process control, short batch times, and low space requirements. It is possible that water could be heated with solar energy to the target temperature of 122 °F. For now, we recommend the use of a tankless propane water heater. The unit we use in the model can heat the water required for a single batch in about 9 hours, consuming about 25 gallons of propane.



A tankless propane-powered water heater⁹³

Pumping

Extraction liquid will need to be pumped rapidly from the extraction tank into the processing tank. For this, we recommend the use of a gas-powered utility pump. At 158 GPM, the model we use in the model can pump the extraction liquid from a single batch in about 24 minutes.



A gas-powered water pump⁹⁴

⁹⁰ Image source: <https://www.watertankfactory.com.au/water-tanks/r22700-litre-5000-gallon-upright-rainwater-tank/>

⁹¹ Image source: <https://www.grainger.com/product/CALDWELL-Manual-Base-Mounted-Jib-Crane-40M591>

⁹² Image source: <https://www.zoro.com/harrington-manual-chain-hoist-6000-lb-lift-15-ft-cf030-15/i/G8540095/>

⁹³ Image source: <https://www.homedepot.com/p/Westinghouse-11-GPM-High-Efficiency-Liquid-Propane-Tankless-Water-Heater-with-Built-in-Recirculation-and-Pump-WGRGHP199/300358963>

⁹⁴ Image source: <https://www.homedepot.com/p/Generac-5-HP-2-in-Gas-Powered-Semi-Trash-Water-Pump-with-Hose-Kit-6822/206275161>

Filtration

Before pigment formation, the extraction liquid will need to be filtered to remove any plant material, dirt, or other particulates that would contaminate the final product. For this, we recommend a cartridge filter, which involves a permanent filter housing and disposable filters.



A cartridge filter for filtering liquid going from the extraction tank to the processing tank⁹⁵

Once pigment has formed and settled, excess liquid can be drained off the top until the silty layer that will have formed at the bottom of the processing tank is reached. The remaining slurry of water and indigo can be pumped with a small pump to further dewatering steps. We expect about 280 gallons of

this slurry per batch. This slurry can be optionally rinsed in acid solution to remove impurities before dewatering. While many methods may be used for dewatering the pigment, we recommend a simple approach using conical gravity filters. These are often used in making herbal extracts and come in a variety of mesh sizes. We found that 25 micron mesh size functioned well for our purposes. Draining is slow, with a single filter batch taking a few days to drain to a wet clay-like consistency. We estimate that if 3 days are required to drain a filter and 40 days are allotted for filtration per harvest, 2.5 acres of indigo could be serviced with a set of 11 filters of 20-gallon capacity.



Cone filters for dewatering pigment slurry⁹⁶

After the pigment slurry has been sufficiently dewatered, it can be further dried in dehydrators, ground, and packaged. It may also be desirable to sell

indigo paste rather than indigo powder, and this can be produced by omitting the full drying step.

ESTIMATED COSTS

We modeled the costs for each piece of equipment in the system we propose along with the labor necessary to engineer, build, and startup the system. In total, we expect the system to require the following capital investment:

Total Cost:	\$68,145
Parts & Materials	\$37,224
Engineering	\$29,600
Other Labor	\$1,320

After a first system is built, we estimate that any subsequent systems would cost around \$52,000 to produce, as much of the engineering and design work would have already been completed on the first unit.

Our recommendations for planting and harvesting equipment can be found in a separate report. When including all capital expenditures from these recommendations, we model the total cost to implement a single 2.5-acre scale indigo planting, harvesting, and water extraction system as follows:

Capital Expenditure	
Total	\$103,686
Planting and Harvesting	\$35,541
Water Extraction System	\$68,145

⁹⁵ Image source: [https://www.grainger.com/product/FULFLO-Cartridge-Filter-Vessel-38XL35?breadcrumbCatId=3629&s_pp=false&picUrl=/static.grainger.com/rp/s/is/image/Grainger/38XL31_AW01?\\$smthumb\\$](https://www.grainger.com/product/FULFLO-Cartridge-Filter-Vessel-38XL35?breadcrumbCatId=3629&s_pp=false&picUrl=/static.grainger.com/rp/s/is/image/Grainger/38XL31_AW01?$smthumb$)

⁹⁶ Image source: <https://boldtbags.com/product/large-cone-3-bag-kit/>

Compost System

In this section we propose a detailed design for a semi-automated indigo compost system. This design is used in the economic analysis presented in the next section.

SYSTEM DESIGN AND OPERATION

As an alternative to the sukumo-inspired method currently employed in

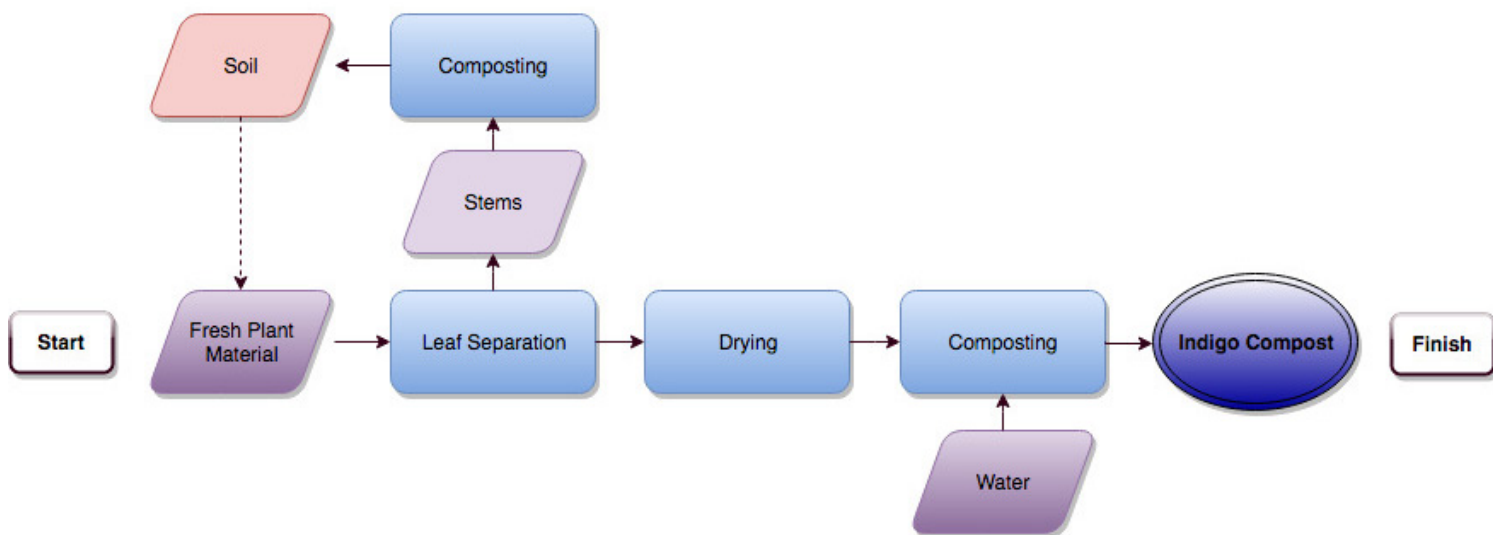
Northern California, we propose a semi-automated approach that uses modern equipment in place of manual steps. As much as possible we have identified equipment used in other agricultural industries that could be applied to indigo compost production with little or no modification.

The basic process is to 1) chop fresh plants with a chipper, 2) winnow the fresh leaves from the stems using

an industrial winnowing machine, 3) dry the leaves using an industrial dryer, 4) partially rehydrate the leaves, 5) compost the leaves in an industrial composting machine, and finally 6) dry the finished compost in the same dryer used earlier. A review of each process step and piece of equipment follows.

Indigo Compost Process

Dotted arrows indicate opportunities for semi-closed or closed-loop cycling. (Diagram by N. Wenner)



Chopping

- Fresh (or partially dried) indigo plants are fed into a chipper.
- The exhaust from the chipper is captured and sent to the next step of the process. The simplest version of this would be ducting leading into an elevated bag or other container that has a feed valve to a conveyor leading into the next step, the winnowing machine.
- Many suppliers exist for suitable chipper machines. Further research will be necessary to determine the ideal model, however the gas-powered unit shown is a good proxy, and we use this unit in the economic modeling.



A gas-powered chipper for cutting up indigo for the winnowing step⁹⁷

Winnowing

- Chopped plants are conveyed into a winnowing machine that uses airflow to separate the denser stem pieces from the lighter leaf material. The stem pieces contain little or no indigo precursors. They are gathered in a bin and can be composted separately and applied back to the land.
- Winnowed leaf material is gathered into a separate bin, which is emptied periodically into the next piece of equipment, a dryer.
- There are multiple domestic and international vendors for winnowing equipment. There are centrifugal types, rotary drum types, and linear drop types. Some of this equipment is used for separating mint leaves from stems, tobacco leaves from stalks, and in other similar applications for plants in both dry and fresh form.
- For the sake of this report, we have assumed the use of a conveyor-fed rotary drum winnower available from a Chinese supplier. More research would be necessary to identify the ideal type of winnowing machine and specific model.



Drying

- This step is intended to render the fresh leaves shelf-stable and ready for the composting step.
- The drying could be completed with many methods, including linear or multi-stage belt dryers, industrial clothes dryers, large drying/dehydration rooms, or in greenhouses with racks.
- For the sake of this report we model the use of a rotary drum dryer used in the green tea industry, available from a Chinese supplier (image below⁹⁸).
- After drying, leaves are removed and stored in large bags or other containers. The dry leaves can be shelf-stable for many months or even years in this form if kept in a cool, dry, and dark environment.



⁹⁷ Image source: <https://www.homedepot.com/p/Brush-Master-4-in-15-HP-420cc-Commercial-Duty-Chipper-Shredder-CH4M17/205571922>

⁹⁸ Image source: https://www.alibaba.com/product-detail/Stable-and-secure-tea-leaf-drying_60697302673.html?spm=a2700.7724857.main07.1.644ab9df7rOQ12

Composting

- The composting step is the main bottleneck in the process given long process times. We recommend an industrial composting machine for faster production time and lower labor costs as compared to other methods. Using such a machine, we expect each batch to take 3-4 weeks to complete with little or no labor beyond loading and unloading the batch.
- The process controls of the composter should allow for control of temperature, air-flow, agitation/mixing, and moisture content.
- For the sake of this report, we have modeled the use of the Tidy Planet Rocket A700 composter, which is typically used for processing food

waste from markets and restaurants. Per batch, this composter can handle dry leaves from a single harvest of about 0.3 acres of indigo. At 3 weeks per batch, it could process about 17 batches per year if run continuously, serving about 2.5 acres with 2 harvests per year.

ESTIMATED COSTS

We modeled the costs for each piece of equipment in the system we propose along with the labor necessary to engineer, build, and startup the system. In total, we expect the system to require the following capital investment:

Total Cost:	\$115,831
Parts & Materials	\$90,961
Engineering	\$13,440
Other Labor	\$900

After a first system is built, any subsequent systems would cost around \$95,000 to produce, as most of the engineering and design work would have already been completed on the first unit.

Our recommendations for planting and harvesting equipment can be found in a separate report. When including all capital expenditures from these recommendations, we model the total cost to implement a single 2.5-acre scale indigo planting, harvesting, and compost system as follows:

Capital Expenditure	
Total	\$151,372
Planting and Harvesting	\$35,541
Compost System	\$115,831



Harvesting indigo by hand at Fibershed's 2016 demonstration farm (Photo by Paige Green)

Economic Modeling

IN THIS SECTION we review the results of economic modeling for the compost and water extraction systems proposed and modeled in the previous sections.

Water Extraction Process

The break-even price of a product represents the price at which that product would need to be sold to recover all the costs of production. In our economic modeling, we attempted to capture all possible costs of production, including direct labor, direct materials and services, and indirect labor and services.

In our model, the break-even price for pigment produced with the proposed water extraction system decreases with scale up to the maximum scale of production, 2.5 acres. At that scale, the break-even price is \$190 for 40% pure pigment, corresponding to a pure pigment price of about \$479/lb. Stony

Creek Colors sells natural indigo from *Persicaria tinctoria* in powder and paste form. Their 40% indigo powder sells at an equivalent pure indigo price of about \$215/lb, and their 12% indigo paste sells at an equivalent pure indigo price of about \$442/lb, both of which are significantly lower than the break-even price we identify.⁹⁹ Indigo retail prices from international producers can range from pure indigo equivalent prices of about \$100/lb to \$200/lb.

To pay back a zero-interest loan on the capital expenditure required to build out a planting, harvesting, and water extraction system (\$100K) in about 10 years, one would need to sell 40% purity indigo powder at a price of about \$250/lb, which is equivalent to a pure indigo price of \$625/lb.

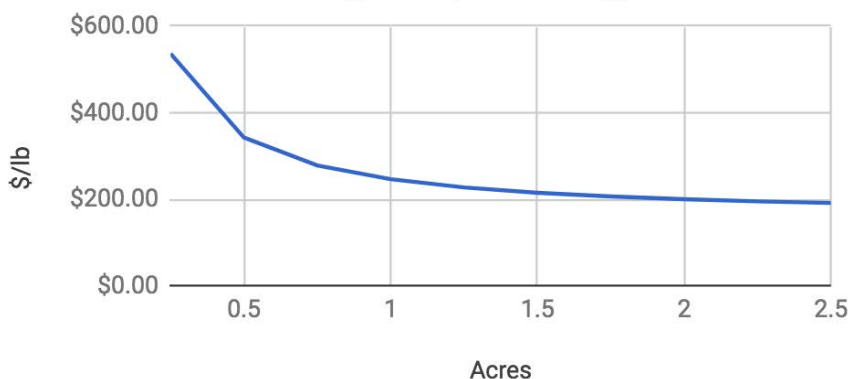
Modeling pigment sales at this price point and production at the 2.5-acre scale, we reach the following income statement:

Annual Income Statement	
Revenue	
Sales	\$41,433
SUBTOTAL:	\$41,433
Less COGS	
Direct Labor	\$11,690
Direct Materials	\$11,814
SUBTOTAL:	\$23,505
GROSS PROFIT	\$17,929
Less Op-Ex	
Indirect Labor & Services	\$8,239
SUBTOTAL:	\$8,239
NET PROFIT	\$9,690
Pre-Tax Profit Margin	23.4%

At the same price point and scale of production, an individual farmer might expect to earn the following in annual income:

Individual Income	
Direct Labor	\$9,140
Indirect Labor	\$7,014
Profit	\$9,690
TOTAL	\$25,844

Break-Even Price for Pigment (40% Purity)



⁹⁹ Stony Creek Colors “Natural Indigo Dye” (<https://dye.farm/products/natural-indigo-dye>)

Compost Process

The break-even price for indigo compost levels out at approximately \$7/lb, corresponding to a pure indigo price of about \$221/lb, which is well within the range of pure indigo retail prices from Stony Creek Colors (\$215/lb - \$442/lb).

Modeling indigo compost production at a scale of 2.5 acres and sales at a price of \$12/lb (corresponding to a pure indigo price of \$375/lb), we reach the following income statement.

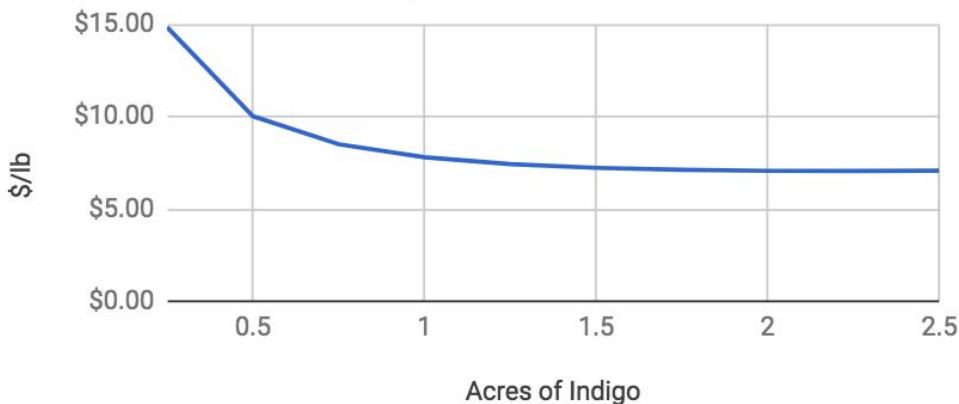
Annual Income Statement	
Revenue	
Sales	\$78,454
SUBTOTAL:	\$78,454
Less COGS	
Direct Labor	\$18,165
Direct Materials	\$19,822
SUBTOTAL:	\$37,987
GROSS PROFIT	\$40,467
Less Op-Ex	
Indirect Labor & Services	\$8,239
SUBTOTAL:	\$8,239
NET PROFIT	\$32,228
Pre-Tax Profit Margin	41%

At the same scale and price-point, an individual farmer might expect to earn the following in total annual income:

Individual Income	
Direct Labor	\$15,015
Indirect Labor	\$7,014
Profit	\$32,228
TOTAL	\$54,257

The operating expenses in this model do not include interest on loans. With zero interest and applying all profit toward the capital expenditure required to build out a planting, harvesting, and compost system (\$150K), the payback period at the given scale and price-point would be about 4.7 years.

Break-Even Price for Indigo Compost



Discussion

The break-even pure indigo price from pigment (\$479/lb) is about 2.2 times that of compost (\$221/lb).

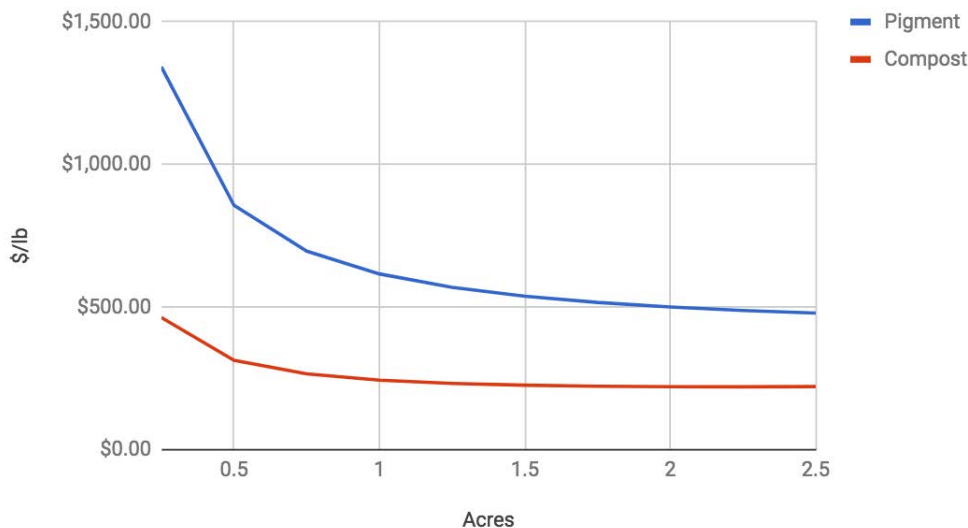
At the 2.5-acre scales, we would expect to produce about 6,500 lbs of indigo compost per year with a compost system or about 170 lbs of 40% purity pigment per year with a water extraction system, capable of dyeing 5,500 lbs of cotton or 1,500 lbs of cotton respectively.¹⁰⁰ At the break-even prices (\$7/lb for compost and \$190/lb for 40% pigment), we would expect dye to cost about \$8/lb of cotton for compost or \$20/lb of cotton for pigment, meaning that the cost of pigment would be about 2.4 times that of compost for a given dyeing capacity.

Clearly, compost has the economic advantage in terms of cost for a given dyeing capacity and in the proximity of its break-even price to other price-points in the market. There is some question, however, regarding the market size available to compost. Large scale producers and home dyers alike may find indigo pigment to be superior to compost in considerations of familiarity, simplicity, uniformity, and predictability. Certainly, large-scale dyeing with compost using fermentation would present many challenges, and it is unclear how well the improvements we propose using benign chemical reduction (e.g. fructose) scale to the commercial level. That being said, if dyeing with compost can be scaled, one textile

mill in Northern California, Huston Textile Company, expects to dye enough material with natural indigo to require about 2.5 to 4 acres of indigo if using the compost process, indicating ample market for at least a single producer.¹⁰¹

It is possible that increased plant yields could improve the viability of the heated extraction process. For example, if annual plant yields are increased to that found in central Italy (about 104,000 lbs/acre/yr)¹⁰², the maximum capacity of the system we propose goes down to 1 acre, and at that acreage the break-even price for 40% pure pigment is \$119/lb, or \$297/lb for pure pigment. At a retail price of \$150/lb for 40% pigment (\$375/lb for pure pigment), net profit would be about \$5000/yr.

Break Even Price for 100% Pure Indigo



¹⁰⁰ According to dye utilization rates states in a previous section

¹⁰¹ Personal communication

¹⁰² Bechtold, T ; Mussak, R (2009) "Handbook of Natural Colorants"

Summary and Conclusions

WE HAVE PRESENTED in this report a study of the technical, environmental, and economic factors involved in indigo dye production from *Persicaria tinctoria* with the aim to support increased farm-scale indigo production in the Northern California fibershed and beyond. Two main approaches to dye production, the compost method and the water extraction method, were presented and compared. The processes were discussed in detail, and particular designs were proposed. These systems were modeled and compared on economic bases.

While the water extraction method is more complex than the compost method and in many cases has a larger environmental footprint, the dyestuff produced can be much more accessible for artisanal and commercial producers alike. This motivated exploration to optimize the process and to minimize its negative environmental impact.

While the compost method as currently practiced in Northern California has many attractive qualities, it is currently limited in scalability by issues of process timing, process control, and high labor content, motivating the exploration of possible tools and methods for reducing cost and increasing efficiency. In this report we identified and recommended concrete improvements to the process in the winnowing, drying, composting, and dyeing steps.

For water extraction, we recommended the heated water extraction approach using calcium hydroxide as an alkalizer and carrying out greywater treatment with atmospheric carbon dioxide neutralization. This production process is a highly closed-loop process, potentially closing water, nutrient, and lime cycles on-site and producing minimum negative externalities.

Calcium hydroxide is the most promising candidate as an alkalizer due to the relatively benign method of its manufacture, its low cost, its dual functions as an alkalizer and flocculant, the relatively benign nature of the greywater produced, and the opportunities it presents for simple and effective greywater treatment and cycling. While the greywater from the use of calcium hydroxide would have little or no negative effect if applied to agricultural lands, we found that this could not be done while maintaining organic certification. We chose heated water extraction over fermented water extraction for increased process control, shorter batch times, and greater mobility.

Based on both firsthand experimentation and on reports from the EU-funded Spindigo Project's heated water extraction efforts, we expect the system we modeled to produce about 66 lbs of 40% purity pigment (27 lbs of pure pigment) per acre, enough to dye approximately 630 lbs of cotton (or about 450 pairs of jeans) per acre. It is possible that pigment yields could be greatly improved by increasing the yield of plant material per acre. In our economic modeling, we erred, however, on the side of caution, using only values for plant yield, pigment yield, and pigment purity that we had actually achieved.

We estimated that the compost system we proposed could produce 2615 lbs of 3.2% purity compost (84 lbs of pure pigment) per acre, enough to dye approximately 2,200 lbs of cotton (or about 1,500 pairs of jeans) per acre. Thus, compared to water extraction, the compost process could produce about 3.1 times the quantity of pure indigo pigment from a given acreage, or about 3.5 times the dyeing capacity.

We presented designs for water extraction and compost systems, finding the capital expenditure to implement a first iteration of each to be about \$100,000 and \$150,000, respectively. Both of these figures include approximately \$35,000 investments in planting and harvesting equipment, the details of which are explored in a separate report. We designed these systems for a maximum scale of 2.5 acres, which represents a good balance of technical and economic feasibility for individual farmers/producers.

In the economic modeling of these proposed systems, we showed the break-even cost for pure indigo from the water extraction process to be about 2.2 times that of the compost process, or about 2.4 times the cost for a given dyeing capacity. At 2.5 acres, the breakeven price for pigment from water extraction was about \$190/lb for 40% pure pigment, corresponding to a pure pigment price of about \$480/lb. The only other domestic producer of indigo, Stony Creek Colors, sells natural indigo at equivalent pure indigo prices of \$215/lb - \$440/lb, and retail prices from international producers can range from pure indigo equivalent prices of about \$100/lb to \$200/lb. Given the high break-even price of pigment from the system we modeled, we find the production of indigo pigment from the heated water extraction process to be technically feasible but not economically viable.

This aligns with the results from the Spindigo Project, which similarly found a heated water extraction system to be "impractical" due to "a lack of sufficient commercial demand from the textile industry, and technical problems with the extraction which lead to a significant proportion of the potential indigo present in the crop not

being recovered. This lead to lower final yields, lower purity, and high unit costs of the product.¹⁰³

That being said, possible increases in plant and pigment yields could have significant impacts on the economic viability of the heated water extraction system we propose, and the system deserves continued consideration as maximum yields are reliably understood.

The compost system appears to be both technically and economically feasible, with a break-even price for 3.2% purity compost at approximately \$7/lb, corresponding to a pure indigo price of about \$220/lb. Modeling production at a scale of 2.5 acres and sales at a price of \$12/lb (corresponding to a pure indigo price of \$375/lb), a producer would expect to earn about \$32,000 per year in net profit at a 41% profit margin, or about \$54,000 per year when including wages from direct and indirect labor. If all profit was applied to pay back a zero-interest loan on an initial investment of \$150,000, the payback period would be about 4.7 years.

Clearly, compost has advantages in terms of cost for a given dyeing capacity and the proximity of its break-even price to other price-points in the market. That being said, there is a question of market size. Indigo compost may have a significantly smaller market

size than pigment given the greater ease and accessibility of dyeing with pigment. If this can be overcome at scale, however, demand for natural indigo in Northern California is already ample for at least a single producer, with one textile mill, Huston Textile Company, expecting to dye enough material with natural indigo to require about 2.5 to 4 acres of indigo when using the compost process.¹⁰⁴

While we did not explore possibilities for fermented extraction systems in this report, it is possible that such a system would give significantly higher yields and improved economic feasibility compared to the heated water extraction system we proposed. Data is scarce, but one study of fermented extraction claims pure indigo yields that are 3.7 - 5.8 times what we found with our own heated water extraction experiments.¹⁰⁵ While a fermented extraction system would likely require a larger investment, a permanent installation, and less predictable processing, the higher yields certainly suggest further consideration. Moving forward, we recommend validating expected yields for fermented extraction and potentially designing and modeling an appropriate system.

In charting a path forward, it is useful to consider the global context. The global production of synthetic indigo was about 180 million pounds per year

in 2010¹⁰⁶, which represents about 15% of global dye production for cotton.¹⁰⁷ Replacing this production with natural indigo from the compost process would require about 2.1 million acres of indigo, or about 3,300 square miles, which is almost twice the land area of Sonoma County, California. This is certainly a large area, but perhaps not unreasonable when considered spread throughout the globe. That being said, synthetic indigo sells at prices around \$2.50/lb for purities around 95%. With pure indigo equivalent prices from indigo compost at about \$220/lb, natural indigo would cost more than 80 times the price of synthetic indigo. Even natural indigo from international producers (with pure indigo prices around \$100/lb) would cost about 40 times the price of synthetic indigo. Clearly, natural indigo cannot serve as a one-to-one replacement for synthetic indigo in industrial production.

Of course, replacing synthetic indigo may not be the most important goal. If the average American continues to own about 7 pairs of jeans¹⁰⁸, the way those jeans are produced is not the only problem worth working on, and significant impacts could be made by focusing on shifting culture and our patterns of consumption. Part of that shift is bringing production home, and part is paying the true cost of what we wear.

¹⁰³ European Commission “Sustainable Agriculture, Fisheries, and Forestry: Research results 1998-2006”

¹⁰⁴ Personal communication

¹⁰⁵ Shin, Y. et al. (2012) “Process Balance of Natural Indigo Production based on Traditional Niram Method”

¹⁰⁶ Franssen M. et al. (2010) “Industrial Biotechnology in the chemical and Pharmaceutical Industries”

¹⁰⁷ Ghaly, A. et al. (2014) “Production, Characterization and Treatment of Textile Effluents: A Critical Review”

¹⁰⁸ Statistics Brain “Denim Jeans Industry Statistics” (<https://www.statisticbrain.com/denim-jeans-industry-statistics/>)

A Vision of the Future

We envision a future where indigo planting and harvesting equipment is shared among a group of farmers in a fibershed region, allowing them each to grow an appropriate acreage of indigo while minimizing capital costs.

Multiple producers could work cooperatively to produce indigo compost with systems like the one we describe in this report, selling this dyestuff to artisans and even larger-scale dyehouses. When not being used for indigo production, equipment like planters, harvesters, winnowers, and dryers could be used for other crops.

As markets are established and understood and as more information on expected yields from water extraction processes is gathered, heated and fermented water extraction methods could be revisited, potentially providing high quality pigment to a large market of both artisanal and commercial producers.

Partnerships with downstream producers in a given fibershed's network such as dyers, weavers, cut-and-sew operations, and designers would allow for local production of indigo-dyed garments such as shirts, jeans, and cloth. Artisanal dyestuffs, commercial dyestuffs, and dyed textiles would represent three levels of indigo products, suiting a variety of users and needs and supporting a robust and diverse network of producers. This model and all the equipment could be replicated in other fibersheds around the world.

We have completed a detailed plan and estimated time, labor, and costs to implement both compost and water extraction systems in the Northern California fibershed. If you are interested in investment or otherwise supporting this project, please contact us at office@fibershed.com.

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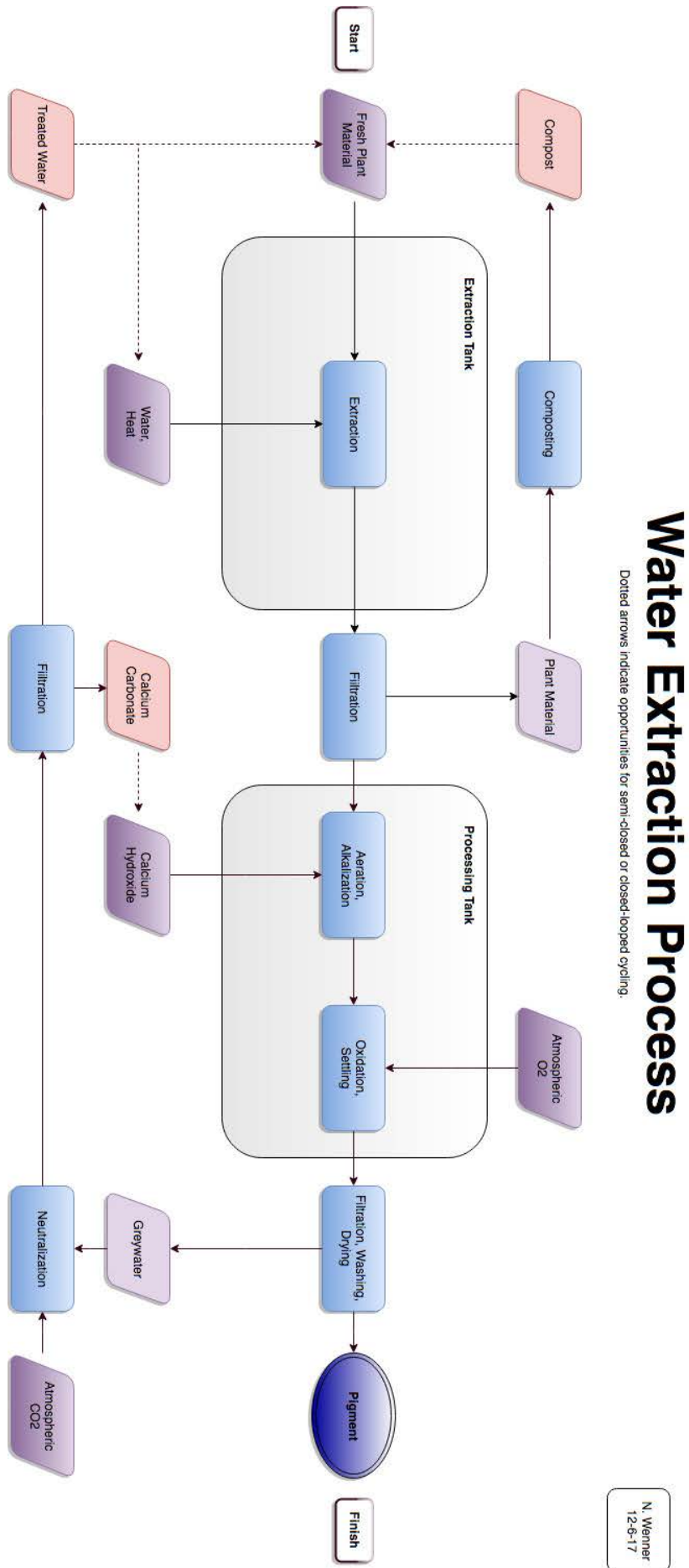
We give thanks to the generations of humans throughout the world that developed and shared the traditions of natural dyeing, working in relationship to the land that supported them.

We give thanks to the indigo plants themselves, who offer such beauty into the world.

And we give thanks to the wonderful system of life that supports us all. May our efforts give back in some small way and support the generativity and resilience of all.



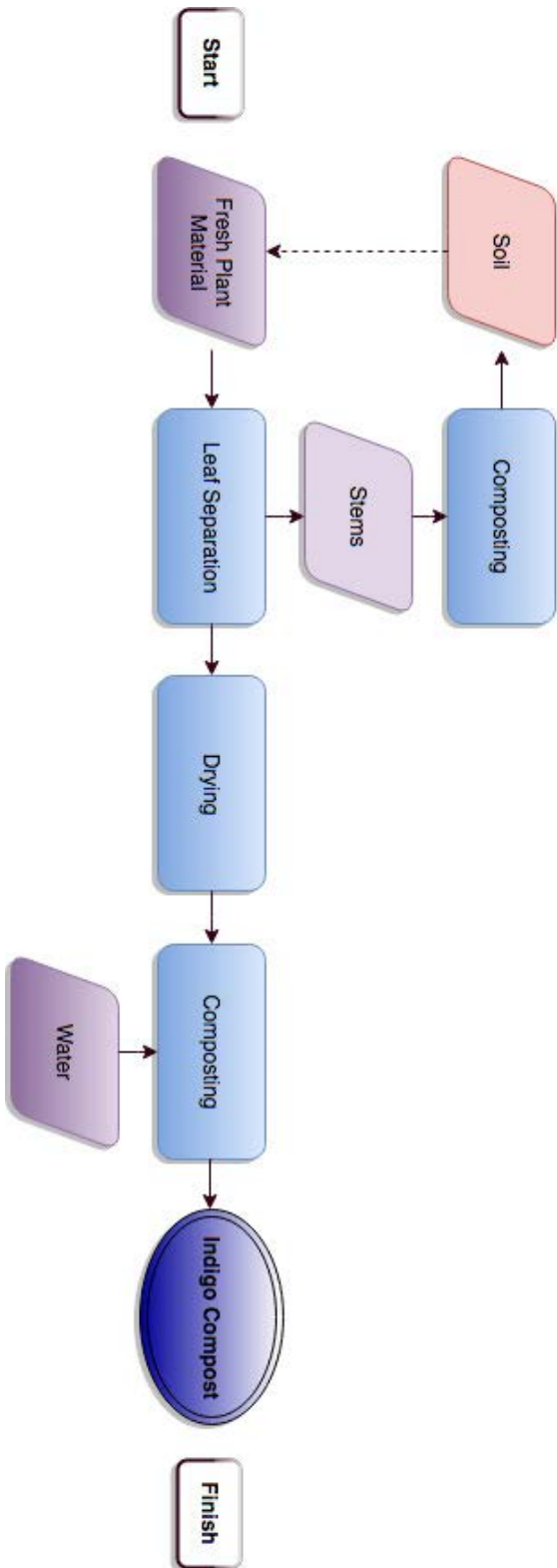
Indigo in bloom (Photo by Paige Green)



N. Weller
12-6-17

Indigo Compost Process

Dotted arrows indicate opportunities for semi-closed or closed-looped cycling.



N. Wenner
12-5-17