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Blue dyed textiles in Early Iron Age Europe: Accessible or exclusive?

Abstract
Evidence for blue dyed textiles becomes widespread in Europe during the first millennium BCE. The dyestuff was likely dyer's woad - *Isatis tinctoria* L. While archaeologists have done much to understand the dyeing process, archaeobotany and chemical analysis of woad dye, there remains a question as to how accessible blue colour textiles were at this time. The aim of this research is to investigate the accessibility or exclusivity of woad dyed blue textiles in this period in terms of the resources, knowledge and skills required to produce them by asking the question "how many woad plants does it take to dye 1 kg of wool yarn blue?"

Keywords: Blue, dyeing, *Isatis tinctoria* L., woad, wool, textile, first millennium BCE, Iron Age, Mediterranean, experimental archaeology

Blue textiles and dyer's woad (*Isatis tinctoria*) 1000-500 BCE Europe

Blue dyed textiles are known from at least the second millennium BCE in Egypt and Europe although evidence becomes more frequent during the first millennium BCE (Wild & Walton Rogers 2003, 25-26; Cardon 2007, 374; Hofmann-De Keijzer et al. 2013, 143-145). One source of blue dye is natural indigo pigment, attained from the chemical synthesis of indigo precursors in leaves harvested from a range of different plant species, genera and families (Angelini et al. 2006, 285). In this paper, the terms "indigo precursors" or "indigotin" are used to discuss dye chemistry, and "indigo pigment" when focusing is on the dyestuff. The research and experiments reported here were only concerned with the woad plant (*Isatis tinctoria*). No products from tropical indigo (*Indigofera tinctoria)* were used as this plant is not relevant to the archaeological period and place in question.

Isatis family plants produce indigo precursors (indican, isatan B, and other isatans), which are extracted from the leaves and used to make indigo (Angelini et al. 2006, 286). Chemical analysis of dye in archaeological textiles detects the presence of indigotin. However, it cannot identify plant species (Angelini et al. 2012, 286). On the basis of its botanical presence in the region, *Isatis tinctoria* L is believed to be the source of an indigoid blue dye found in textiles in the first millennium BCE in Europe and the Mediterranean basin (Zohary et al. 2012, 167). Commonly known as dyer's woad, it belongs to the mustard family (*Brassicaceae*) (Hurry 1930, 1; Balfour-Paul 1998, 93; Zohary et al. 2012, 166-167). The geographical origin of *Isatis tinctoria* L. is debated; its native origin is usually attributed to Asia or southwest Asia, and areas of south/southeastern Europe (Zohary et al. 2012, 166; Guarino et al. 2000, 396).

Archaeological evidence of *Isatis sp.* seeds and accounts in classical literature demonstrate that woad, along with other plant dyes such as madder, was grown in the Mediterranean, temperate Europe and southwest Asia from the first millennium BCE (Körbe-Grohne 1987; Zohary et al. 2012, 166; Hofmann-de Keijzer et al. 2013, 143-145). Traces of indigotin are found in textiles across Europe from the late second, and more frequently from the mid-first millennium BCE. For example, indigotin is detected in a sizeable proportion of textiles from the Middle Bronze Age (1458-1245

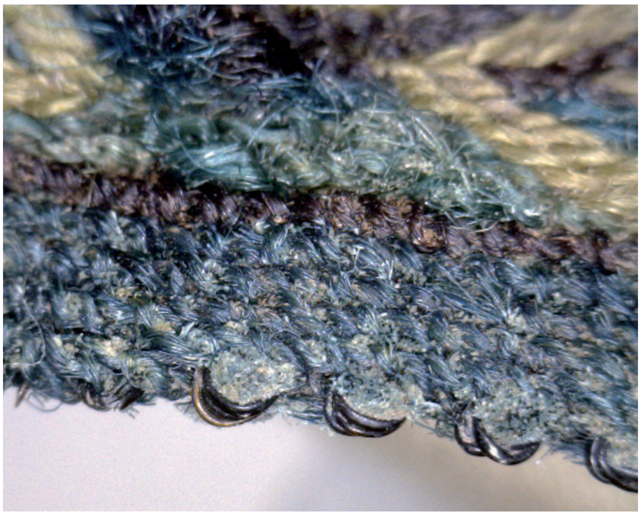


Fig. 1: Tablet woven band with several shades of blue yarn. Hallstatt Textile 123 (Image: Margarita Gleba, courtesy of Natural History Museum Vienna)

cal. BCE) and Early Iron Age deposits at the Hallstatt salt mines, Austria (Grömer et al. 2013, 451-452; Hofmann-de Keijzer et al. 2013, 142-143) (fig. 1). The borders of two garments from a well-furnished man's burial, Tomb 89, Lippi Necropolis in Verucchio, Italy, circa 725 BCE to 675 BCE were dyed with indigotin in combination with madder (*Rubia peregrine L.*) or tannins (Stauffer et al. 2002, 216; Stauffer 2012; 247-250). Wool stitching in clothing found at Riesenferner/Vedretta di Ries, Italy, 795-499 cal. BCE has a blue colour, chemically identified as indigo pigment (Bazzanella et al. 2005). The elaborate princely burial of Eberdingen-Hochdorf, Germany, circa 540 BCE, has splendid coloured textiles, including those dyed blue and red (Walton Rogers 1999; Banck-Burgess 2014, 150). There are also blue textiles shown in pictorial representations. The colourful paintings inside the Etruscan tombs of Tarquinia, Italy, circa 550 BCE, depict men and women wearing vivid plain and patterned blue and green (potentially yellow/blue dye combination) textiles (Steingräber 1986) (fig. 2). While in archaic Greece, the robes and patterned borders of garments on marble statues of young women, possibly goddesses (circa 520 to 500 BCE), are painted with blue and green pigments, presumably representing blue or green textiles (Catalogue 2012, 32, 40).

There has been significant research on the colour of woad dyed textiles and the dye process (Hartl & Hofmann-de Keijzer, 2005; Hartl et al. 2015). However, in contrast to the attention given to the exclusivity of shellfish purple dye for textiles (Edmonds 2000; Ruscillo 2005; Landenius Enegren & Meo 2017), woad blue textiles of this period are rarely considered

Fig. 2: Blue and green clothing, Tomb of the Lioness, Tarquinia, Italy circa 550 BCE (Image: Susanna Harris, by kind permission of Polo Museale del Lazio – Tarquinia (VT), Necropoli di Monterozzi)

Planting in early spring
↓
First leaf harvest in early to late summer
↓
Second & subsequent leaf harvests in autumn
↓
Prepare leaves in one of the following ways:
↓

1.Use fresh leaf	2. Pulp leaves, mould and dry to make into woad balls ↓ Crush, soak or macerate woad balls in preparation for the dye vat.	3. Cut, crush, macerate leaves in warm water, follow precipitation and aeration processed to make into woad powder (woad pigment)

↓
Prepare dye solution
↓
Prepare vat
↓
Add dye solution to vat
↓
Dip fibres, yarns or textiles in vat
↓
Repeat dipping to desired shade
or until vat is exhausted
↓
Refresh vat with new dye solution

Table 1: *Chaîne opératoire* of the main stages of growing and harvesting dyer's woad (*Isatis tinctoria* L.), three alternative forms of dye stuff preparation, vat preparation and dyeing

by archaeologists in terms of their accessibility or exclusivity. Yet, this is crucial for understanding the significance and value of blue textiles. Long distance connections and the competitive relationships of early urban living across the Mediterranean and central Europe in the mid-first millennium BCE created the desire for more, and more expensive possessions. The expense and exclusivity of fine, colourful textiles make them a ready form of personal comparison. They may be a means to justify and legitimise the dynamics of power (Harris 2017, 683). This raises the question: were certain colours more accessible than others?

Methodology

By posing the question "how many woad plants does it take to dye 1 kg of wool yarn blue?", this research aims to investigate the accessibility or exclusivity of woad dyed blue textiles by considering the resources, knowledge and skills required to produce them. This question was investigated through interviews with small-scale commercial dyers, published literature and experimental dye vats. The *chaîne opératoire* of woad dyed textiles (*Isatis tinctoria* L.) was analysed in order to investigate the accessibility of textiles dyed blue. This analysis considered the resources, knowledge and skills required at each stage of the process using three lines of evidence: literature on woad growing, processing and dyeing; interviews with small-scale commercial dyers (Brenac, Howard and Lambert) and one dyer working in a professional workshop (Roberts), all of whom were asked qualitative and quantitative questions about their experiences growing and dyeing with woad; and the use of experimental dye vats to investigate the quantity of woad plants required to dye a specified weight of wool yarn blue. The use of the vats permitted actualistic process and function experiments (as in Outram 2008, 2) using accurate materials (single spun wool yarns, dye ingredients) to test the hypothesis that is both quantitative (number of plants, weight of wool) and qualitative (knowledge and skills). It was recognised that other colours can be achieved with woad vats (Hartl 2015, 581, fig. 15) but the concern here was with achieving blue.

Evaluating the *chaîne opératoire* of woad dyed yarns

The main stages of the *chaîne opératoire* of woad growing, processing and dyeing are outlined in table 1.

Fig. 3: Modern seeds of dyer's woad, *Isatis tinctoria* (Image: Patricia Hopewell)

From woad seed to plants

Historically, woad was grown across Europe in a variety of climates and terrains. Woad seeds should be sown in a rich, alkaline, well-drained soil for robust plant growth (fig. 3). The tendency of woad to leach the soil of all goodness led to it being a banned crop in some areas of 16th century England (Hurry 1930, 30). A biennial plant, the source of indigo pigment in *Isatis tinctoria* is present during the first year of growth when the leaves are at the rosette stage (Angelini et al. 012, 285), and a plant can be harvested multiple times. In southern Italy, woad plants were sown in levelled, furrowed ground in autumn (October) or early spring (February). The plants were weeded, hoed several times, and thinned if they had been planted too closely (Guarino 2000, 398). The first leaf harvest was in early June and repeated up to six times over the next two to three weeks, although the quality of the indigotin in the leaves decreased with subsequent harvests (Guarino et al. 2000, 398). Left to seed, dyer's woad produces ample seeds; in some places woad is an invasive weed. An individual woad plant can measure up to 120 cm in height, and 60 cm in diameter with as many as 90 leaves (Guraino et al. 2000, 395) (table 2). Today's cultivated varieties are typically smaller, and often harvested when they are 25 cm high and with a rosette diameter of around 30 cm (Angelini et al. 2012, 285-295). According to interviews with the growers, depending on a variety of growing factors, the leaf from a woad plant can weigh between 200 g to 700 g (Howard 2019 pers. comm.; Roberts 2018b). The quantity of leaves to one plant depends on many factors, including growing conditions and the health of the plant. A farm in Rochefort, France, cultivates 11,000 to 20,000 plants in one hectare of land (one hectare equals 10,000 m²). The plants measure 30 cm to 40 cm in diameter with 20 to 50 leaves on each plant, with a mean of 25 to 35 (Brenac 2016, pers. comm.). Here, plants are the smaller modern variety. In a good year, there are up to 50 leaves per plant for the first harvest and 30 to 40 leaves per plant for the second harvest. In a poor year, there are as few as 20 leaves per plant (Howard 2019, pers. comm.). However, the size of plant does not guarantee a higher indigotin content. A study of *Isatis tinctoria* cultivation showed that higher air temperatures and radiation coupled with low rainfall and regular irrigation led to a higher isatan B content, the precursor most important for indigo pigment production (Angelini et al. 2012, 289). This correlates well to growers' reports that higher temperatures produce plants with more indigotin content.

From woad plants to dye stuff

Fresh leaves can be used directly or processed through a complex chain of biological reactions that take place during the dyeing process (Cardon 2007, 338-340). In current day practice, dyers prepare the plant in one of three ways: fresh leaf, woad balls or woad powder (also referred to as woad pigment). It is not known which process was used in the first millennium BCE in Europe.

Fresh leaf

The woad leaves are picked from the plant, immersed in water with ingredients such as wood ash, soda ash (sodium carbonate, Na_2CO_3) and urine which create an alkaline liquid and commence fermentation (Balfour-Paul 2011, 102) (fig. 4). Urine was used historically in the dye process but the technique is not widely practiced today.

Woad balls

Wood balls are made by pulping fresh leaves, which are moulded into balls and dried (Cardon 2007, 369; Balfour-Paul 2011, 102) (fig. 5). Historically, leaves or woad pulp balls were left to ferment, a process called couching. In the 19th century, the woad balls were broken up and ground to a powder, whereupon it was sprinkled with water and allowed to ferment for about nine weeks, and turned regularly, with particular care taken regarding the temperature, which should not exceed 52°C (Hurry 1930, 26; Cardon 2007, 369). According to Howard, approximately 500 g of fresh leaf is required for one 60 g/70 g dry weight woad ball (Howard 2019, pers. comm). About seven to ten times the weight of fresh leaf is required to make a woad

Fig. 4: Fresh woad leaves tightly packed in a sealed vessel to ferment (Image: Patricia Hopewell)

ball; a ball equates to around one or two plants' worth of leaf depending on the size of the plant. Woad ball making is an historic practice, and today are only made by contemporary dyers out of interest and curiosity.

Woad powder

Wood powder is commonly referred to as wood pigment being the powdered preparation used today. There is insufficient evidence to suggest which process was used in prehistory. In the experiments, woad powder was used as this is most familiar to the dye experts involved. In present day commercial woad production, the fresh woad leaves are prepared as powder to maximise the indigo pigment yield (fig. 6). The leaves are steeped in hot water at 70 °C to 75 °C for seven to ten minutes to damage the wax surface of the leaves (Stoker et al. 1998, 317) and extract the precursors, indican and isatin B; this leads the production of indoxyl (Cardon 2007, 340-341). After removing the leaves, the water is rapidly cooled to prevent the loss of the indigotin. At 25 °C, calcium hydroxide is added providing the alkalinity required to neutralise the acids produced during fermentation,

Fig. 5: Two prepared woad balls (Image: Patricia Hopewell)

until the solution turns green and the pH is between 10.5 and 11.5. It is then aerated for approximately 20 minutes to precipitate the blue pigment. The mixture is settled overnight. After the surplus water is removed, solid citric acid is added, which releases the indigotin. The mixture should turn blue and the pH falls to between 4 and 5. The solution is again left overnight, any excess water is removed, and the remaining sediment is dried to a powder (Howard 2019, pers.comm.).

According to Howard, approximately 5,000 woad plants or 1 tonne (1,000 kg) of woad leaf is needed to make 500 g of woad powder (Howard 2019, pers. comm.). That equates to approximately five plants or 1,000 g (1 kg) of leaf to make 0.5 g woad powder (table 2). At Bleu de Lectoure, Gers, France, they use 1 tonne of leaf to make 2 kg of powder. This is similar to the 1.9 kg to 2.3 kg of woad powder obtained from 1 tonne of woad leaf referred to by Cardon (2007, 371). According to Brenac (see table 2, 2016, pers.comm.), 1 tonne of leaf produces 1 kg to 2 kg of woad powder. That equates to approximately 1 kg of leaf to produce

Fig. 6: Two woad powders of different strength purchased from The Woad Centre, Norfolk. Both batches of powder are prepared from dyer's woad, *Isatis tinctoria*, which is grown on the farm. Prepared woad powder is also called woad pigment (Image: Patricia Hopewell)

Plant size	Plant weight	Plants grown on 1 ha land	Fresh leaf weight: one woad ball	Number of woad plants to 1000 kg leaf	Weight of leaf: woad powder	Woad powder to dye wool fibre / yarn	Plant require d to dye 1 kg yarn	Geographical location	Source
H 120 cm, Diam. 60 cm	-	-	-	-	-	-	-	Southern Italy	Guarino et al 2000, 395
H 25 cm, Diam. 30 cm	-	-	-	-	-	-	-	Pisa, Italy	Angelini et al 2012, 287
-	700 g	-	-	-	1 kg leaf: 1 to 4 g	1 g dyes 20 g fibre light to mid blue*	-	Birmingham, UK	Teresinha Roberts 2018b, and pers.comm 2018a
-	200 g	-	500 g leaf : 60/70 g woad ball	5,000 plants	1,000 kg: 0.5 kg	-	-	Norfolk, UK	Ian Howard, The Woad Centre
Diam. 30-40 cm	-	11,000-20,000	-	-	1,000 kg: 1- 2 kg	-	250 - 1,000	Rochefort, France	Patrick Brenac, Couleurs de Plantes SAS
-	-	-	-	-	1,000 kg: 2 kg	-	-	Gers, France	Denise Lambert (Anon. *ca.*2016)
-	-	-	-	-	-	10-20 g dyes 200 g light to mid blue*	-	North Wales, Cambridgeshi re, UK	Experimental vats with Helen Melvin & Susanna Wareham

Table 2: Quantity of dyer's woad plants *Isatis tinctoria* L. required to produce dye ingredients based on interviews and published literature

1 g to 2 g of woad powder. For Roberts, 1 kg of woad leaf will produce between 1 g to 4 g of woad powder (Roberts 2018b). From these interviews, it is apparent that 1 kg of woad leaf can produce between 0.5 g and 4 g of woad powder, although for the commercial growers this range is more restricted with 1 kg of woad leaf producing between 0.5 g and 2 g of woad powder. In terms of the number of plants, based on weight of an individual plant between 200 g and 700 g, from 1.5 to 5 woad plants are needed to make 0.5 g to 2 g woad powder.

Dyestuff to blue textiles

The purpose of the experimental dye vats was to recreate the process of dyeing wool yarn with woad to gain quantitative and qualitative results and evaluate the knowledge, skills and resources required to dye textiles blue. The experiments were carried out with experienced dyers Helen Melvin in north Wales and Susanna Wareham in Cambridgeshire, United Kingdom. Dye vats were prepared using three sources of woad: fresh woad leaf, woad balls, and woad powder. Fresh leaves were used from plants grown from seed in Melvin and Wareham's gardens. All woad powder and woad balls were sourced from Ian Howard at The Woad Centre, Norfolk, United Kingdom. All vats were prepared in different parts of the United Kingdom in July with temperatures of approximately 20˚C in north Wales and 25˚C in Cambridgeshire. Woad is insoluble in water; to prepare a fermentation vat today, woad is often chemically reduced to a water soluble form known as leuco-indigo (Hurry 1930, 35; Cardon 2007, 367-377). A reducing agent removes the oxygen from the vat; with the oxygen removed, the indigotin becomes soluble in water. A fermentation process must take place by adding an appropriate substance. Contemporary practitioners use various agents, such as natural sugars from fruit (very ripe pears, bananas, dates, fructose) or wheat bran, medicinal plants or other dye plants (for example, madder, as used in the vats below). To assist in this process, lime (calcium hydroxide, $Ca(OH)_2$) is added as a base for the purpose of controlling alkalinity. Fresh or dry chopped madder roots may be used. However, a larger quantity of fresh madder would be required per weight of fibre. At this point, it becomes an alkaline soluble substance of pH 9/10, commonly called indigo white. Today, woad is manufactured using reducing agents such as sodium

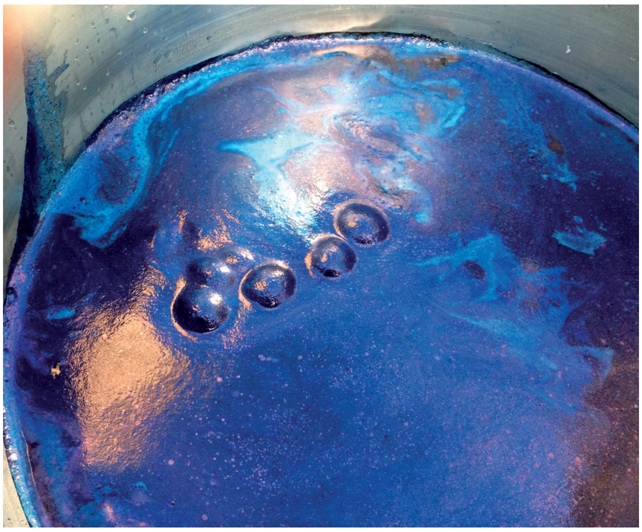


Fig. 7: The woad dye vat (Image: Patricia Hopewell)

hydrosulphite or thiourea dioxide which are added to remove the oxygen from the vat; these chemicals were avoided in the experimental vats.

Single spun, non-pigmented wool yarn was selected from Shetland breed sheep. The yarn was scoured before dyeing to enable the dye to penetrate evenly. Scouring removes the natural lanolin from the sheep by soaking the yarns in a soap solution for several hours then rinsing it well. The quantity of woad and wool were measured for each vat. For the sake of consistency, the aim was to dye the wool mid-blue, Pantone 2915 UP (PANTONE® 2018). This is based on preserved blue dyed yarns from textile fragments from Vedrette di Ries, Italy and Hallstatt, Austria and blue colour cloth and clothing in the Etruscan tomb paintings of Tarquinia (for example, fig. 2). It was important to gauge the shade to a certain degree, as it requires more dye (stronger dye vat and/or multiple dips) to dye a cloth dark blue than light or mid-blue. As all dyers know, it is not possible to precisely control the shade of each dye vat. However, the gradation of blue that can be obtained from a dye vat is well known (Cardon 2007, 58); dyers can judge the depth of colour a vat will dye, and learn to adjust the number of dips or strength of the dye vat to achieve the desired shade (fig. 7 and 8).

In all cases, 200 g of wool yarn was dipped to achieve the target mid-blue colour. The results were recorded up to that point. Beyond that, further yarn could have been dyed but the shade may have changed, and weakened as the vat reached exhaustion. The vat details are documented in table 3.

The experimental vats were not fully successful. Despite working with experienced woad dyers, the dye vats using fresh leaf or woad balls failed. This led to the use of woad powder (*Isatis tinctoria*) produced from woad plants grown at The Woad Centre in Norfolk, United Kindom, a substance with which today's dyers are more familiar.

Vats with fresh leaf

Fresh leaves were picked directly from the plant, tightly packed in glass jars with rubber seals and metal sprung clips to secure the lids, and left to ferment for 21 hours following a published recipe (Wicken 1983). Two of the fresh leaf vats followed a dye process using either wood ash lye and wheat bran or calcium hydroxide (lime) (table 3, Vats 1 and 2). The resulting beige or faint blue did not match the desired shade of mid-blue. The third fresh leaf vat contained human urine, pH unknown, which had been kept under warm conditions for eight weeks, as a fermentation aid. However, no blue colour was achieved (table 3 Vat 3). The poor colour results from the vats using direct dyeing with fresh leaves give credence to the necessity of long natural fermentation processes, which were used in the 16th and 19th centuries, for which the leaves were cut, crushed and subsequently went through a fermentation over several weeks (Hurry 1930, 26). Dyeing with fresh leaf and urine proved challenging, despite being carried out with experienced dyers. Melvin in North Wales had many earlier successes dyeing with urine; in this instance, with a later addition of dates, a blue colour was achieved (table 3, Vat 7). Reasons for the failure of the urine vats could have been insufficient warm weather,

Fig. 8: Wool yarn drying after dyeing different shades of blue (Image: Patricia Hopewell)

insufficient time allowed for the fermentation process, or poor indigotin content in the leaves. Hartl and team also reported a disappointing outcome using urine in north Wales. The process took so long that her urine experiments were discontinued (Hartl et al. 2015, 35). Despite efforts made to maintain optimum conditions, the results with urine were disappointing, as it is considered to be a relatively easy process.

On reflection, given the reports from the commercial growers that it takes 1 kg of woad leaf to produce 0.5 g to 2 g of woad powder, the pale turquoise achieved with the fresh leaf vats was probably due to the low weight of fresh woad leaf (83 g to 300 g) used in these vats, and the resulting weak dye solution rather than a failure of the vat. For this reason, the fresh leaf vats did not provide quantitative results for the calculations.

Vat with woad balls

To prepare the dyebath, the woad balls were crushed, sprinkled with water and left for an hour or so then added to the vat. The crushed balls were left in the vat for the whole dyeing process. Following current dye practices, the process of couching was not followed here, which may be one of the reasons the initial results failed to achieve a blue colour; blue was achieved with the addition of further lime and ripe fruit (table 3, Vat 4). As with the vats using fresh leaves, the vats with woad balls did not result in mid-blue dyed yarn, only light blue. Hence, as with the fresh leaf vats, the woad ball vat did not provide quantitative results for calculations. Similarly, the results from the interviews were not sufficiently clear as to the quantitative results of woad balls to dye outcome.

Vats with woad powder

In two woad powder vats, ripe fruit (pH unknown) was added to aid fermentation. Vats with apples failed as the acid content was too high. Pears and prunes produced good results (table 3, Vats 5 & 6). Vats using woad powder and ripe fruit as a fermentation aid produced suitable blue yarns. Doubling the quantity of woad powder in Vat 6 resulted in darker shades of blue than Vat 5.

As with the fresh leaf with urine (table 3, Vat 3), the woad powder vat with urine as a fermentation aid produced a dull beige colour, improving with the addition of ripe fruit to light blue (table 3, Vat 7). Three woad powder dye vats were undertaken using dyer's madder *(Rubia tinctorum)*, as an aid to fermentation, (table 3, Vats 8, 9, 10). Contrary to expectation, this recipe produced blue dyed textiles, not purple, despite the large ratio of 90 g of madder to 30 g of woad powder.

Lime was added to the vat to control the alkalinity and madder roots were used to aid the fermentation process in the dye vat. It is aerobic bacteria which remove the oxygen allowing the indigo to dissolve. In the dye vat, the madder's role is to help anaerobic bacteria convert the insoluble indigo into indigo white. In the past, aged urine was used extensively as a source of alkali, which is necessary for the reduced indigo (indigo white) to dissolve. The alkali and madder do not help to remove oxygen (John 2016, pers. corresp.). Madder is a versatile plant for dyeing and to aid fermentation and is important for today's natural dyers. Charllotte Kwon at Maiwa Handicrafts often uses madder for its fermentation properties when dyeing reds in organic woad vats (Kwon 2016, pers. comm.). The woad powder vat with ripe pears dyed a mid-blue colour, as did the vats with woad powder, madder and lime.

The vats using woad powder, with either wood ash lye and wheat bran or lime and madder were consistently successful, producing blue yarns. In terms of quantitative results, Vat 5 (table 3) used 10 g of woad powder to dye 200 g of wool light blue; Vat 6 used 20 g of woad powder to dye the same weight of wool yarn a mid to dark shade of blue. Those vats using 30 g of woad powder were not exhausted or dyed to a deeper shade of blue than required. According to Roberts, 1 g of woad powder will dye about 20 g of fibre (Roberts 2018b). This matches a general guide for contemporary dyers that 10 g to 20 g woad powder dyes 200 g of wool (Roberts 2016; Plantes de Couleur 2016).

How many woad plants are required to dye 1 kg of wool yarn blue?

Using the information gathered above, it is possible to attempt to answer the question: how many woad plants are required to dye 1 kg of wool yarn blue? In answering this question, there are three important variables to consider: the size of the woad plants, the quantity of woad powder produced from fresh leaves, and the potency of the dye. In addition, the resources, skills and knowledge required to achieve blue textiles are also considered.

Given the variability in the production processes, four possible scenarios based on the most and least productive results, excluding dye vats that failed (table 4) were assessed. Taking into consideration the results above from the commercial woad growers (summarised in table 2), it typically requires 1,000 kg of woad leaf to make between 0.5 g and 2 kg of woad power. Given a successful dye vat, this is enough to dye between 5 kg and 40 kg wool yarn mid-blue aiming for Pantone 2915 UP. From these results, and assuming that all stages of the process are at their

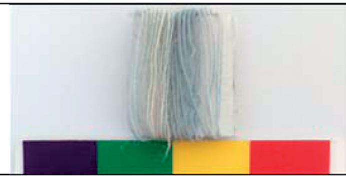
Vat & Practitioners	Ingredients	Dye process	Dips	Dye result on wool
1. Vats with fresh leaf (Melvin/Hopewell)	300 g Fresh woad leaf 1000 ml Wood ash lye 30 g Wheat bran	Pick leaves at first harvest – July/August Crush leaves, macerate in 1000 ml water at 50- 60°C, add wood ash lye (Wood ash is prepared by pouring boiling water over ashes in a bucket, leave to soak for several weeks, skim off the clear lye and discard the sediment). Heat until simmering, allow to rest, vat is now ready for dyeing. Vat maintained at pH 9 - 9.5	1st dip – no colour 2nd dip – 24hrs pale turquoise	
2. Vats with fresh leaf (Melvin/Hopewell)	83 g Fresh woad leaf Lime (calcium hydroxide, $Ca(OH)_2$)	Direct dye. Tear leaves into small pieces, fill 2000 ml jar with leaves, fill to the brim with boiling water, wait for bubbles to appear. Wait 30-40mins, strain off liquid and add 15 ml lime (calcium hydroxide)	1st dip - 2h 2nd dip – 4h	
3. Vats with fresh leaf (Wareham/Hopewell)	200 g Fresh woad leaf 1000 ml Urine aged 8 weeks, pH not known. 10/12 g Soda ash (sodium carbonate, Na_2CO_3) 2 Prunes	Pick leaves at first harvest – July/August crush leaves, macerate in 1000 ml hot water add leaf extract to urine, add soda ash. Add 2 chopped prunes. Daytime temperature maintained at 40° - 50°	After long dip – no colour	
4. Vats with woad balls (Wareham/Hopewell)	2 Woad balls 15 g Soda ash 5/10 g Lime (calcium hydroxide $Ca(OH)_2$) 3 Prunes	Woad balls were crushed initially with a wooden mallet, then rubbed between finger and thumb until fine, add approx. 400 ml cold water to moisten, add 2000 ml water, the local water in Cambridge is hard, at 30°, leave for 1 hour. Add soda ash and 5 g lime, wait 15 mins	1st dip pale yellow beige – 20 mins Add more lime (5g) Add 3 chopped prunes 2nd dip -30mins	
5. Vats with woad powder (Hopewell)	10 g Woad powder 2/3 Ripe pears 15 g Lime (calcium hydroxide $Ca(OH)_2$)	Filter the juice from crushed, boiled fruits by pouring gently through a sieve, (mesh size 6 x 6 mm) put in dye vat at 50°C Put the fruit in a cotton bag and put into the vat, add hydrated woad powder, lime, stir gently several times. When a bronze film occurs with bubbles on top the vat is ready. pH 9-9.5. With the exception of 1st dip, varying shades of pale turquoise	1st dip – 10mins 2nd dip – 30mins 3rd dip – 1hr 10mins 4th dip – 2hr 10	

Table 3: Dye vats using fresh woad leaf, woad balls and woad powder with details of ingredients, process, dipping times and colour outcome on 200 g single spun Shetland wool yarns

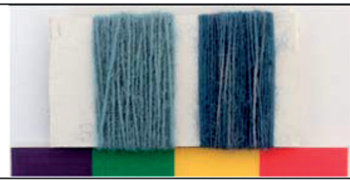
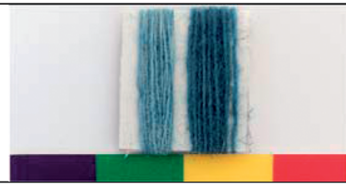
Vat & Practitioners	Ingredients	Dye process	Dips	Dye result on wool
6. Vats with woad powder (Hopewell)	20 g Woad powder 2/3 Ripe pears 15 g Lime (calcium hydroxide $Ca(OH)_2$)	Filter the juice from boiled, crushed fruits, by pouring gently through a sieve (mesh size 6 x 6 mm) add to water in dye vat 50°. Put the remaining fruit into a cotton bag and into the vat, add hydrated woad powder, lime, stir gently several times. When a bronze film occurs with bubbles on top the vat is ready. pH 9-9.5 Increased amount of woad powder resulted in shades ranging from turquoise to dark blue, very satisfactory result.	1st dip – 5mins 2nd dip – 10mins 3rd dip – 15mins 4th dip – 20mins	
7. Vats with woad powder (Melvin/Hopewell)	20 g Woad powder 6000 ml Urine aged for 8 weeks 3 Dates	Add woad powder to warm water and mix well, add to urine, allow to mature for 6 days, pH9, maintain warm conditions at 40°- 50°	1st dip – 2hrs with the addition of chopped dates 2nd dip – 3hrs	
8. Vats with woad powder (Melvin/Hopewell)	35 g Woad powder 60 g Madder, chopped roots 500 ml Wood ash lye 20 g Wheat bran	Add woad powder to 50- 60 °C water and mix well. Put water, madder, bran, and wood ash lye in a pan and boil until a scum appears and the top turns from pink to purple. Cool to 40°, add woad solution. Maintain temperature. Leave until bubbles form on top. pH 9 - 9.5	1st dip – 30mins with the addition of 5 chopped dates 2nd dip – 1hr	
9. Vats with woad powder (Wareham/Hopewell)	30g Woad powder 90g Madder powder 60g Lime (calcium hydroxide $Ca(OH)_2$)	Add madder to cold water, stir heat to boiling, sieve. Put woad powder in plastic jar with pebbles and hot water and shake well to hydrate, add to madder and stir. Sprinkle lime on top, stir gently and leave until liquid is a clear yellow green and bubbles form on top. pH 9-9.5	1st dip – 10mins 2nd dip - 15mins 3rd dip – 20mins 4th dip – 25mins	
10. Vats with woad powder (Hopewell)	10 g Woad powder 30 g Madder powder 20 g Lime (calcium hydroxide $Ca(OH)_2$)	Add madder to cold water, stir heat to boiling, strain through a sieve, (mesh size 6 x 6 mm). Put woad powder in plastic jar with pebbles and hot water and shake well to hydrate, add to madder and stir. Sprinkle lime on top, stir gently and leave until liquid is a clear yellow green. pH 9 - 9.5	1st dip – 5mins 2nd dip – 10mins	

Table 3 (continued): Dye vats using fresh woad leaf, woad balls and woad powder with details of ingredients, process, dipping times and colour outcome on 200 g single spun Shetland wool yarns

Quantity woad leaf	Quantity woad powder	Dye potency	Wool yarn dyed blue with 1000 kg leaf	Ingredients to dye 1 kg wool yarn blue
1,430 large woad plants produce 1,000 kg fresh leaf	to make 2 kg woad powder.	If 50 g powder is enough to dye 1 kg wool yarn	then 1,430 large plants produce 1,000 kg woad leaf makes 2 kg woad powder and dyes 40 kg wool yarn blue.	This means to dye 1 kg wool yarn blue requires 50 g woad power from 25 kg woad leaf of 35.75 large plants.
	to make 0.5 kg woad powder.	If 100 g powder is enough to dye 1 kg wool yarn	then 1,430 large plants produce 1,000 kg woad leaf makes 0.5kg woad powder and dyes 5 kg wool yarn blue.	This means to dye 1 kg wool yarn blue requires 100 g woad powder from 200 kg fresh leaf of 286 woad large plants.
5,000 small woad plants produce 1,000 kg fresh leaf	to 2 kg woad powder.	If 50 g powder is enough to dye 1 kg wool yarn	then 5,000 small plants produce 1,000 kg woad leaf to make 2kg woad powder and dyes 40 kg wool yarn blue.	This means to dye 1 kg wool yarn blue requires 50 g woad powder from 25 kg woad leaf from 125 small woad plants.
	to 0.5 kg woad powder.	If 100 g powder is enough to dye 1 kg wool yarn	then 5,000 small plants produce 1,000 kg woad leaf makes 0.5 kg powder and dyes 5 kg wool yarn blue.	This means to dye 1 kg wool yarn blue requires 100 g woad powder from 200 kg fresh leaf of 1,000 small woad plants.

Table 4: Four possible scenarios for the number of woad plants required to dye 1 kg wool yarn blue based on the data gathered in this paper. Three variables are considered: 1) size of the woad plant, 2) quantity of woad powder produced from fresh leaf, 3) potency of the dye

most productive, it could take as few as 36 large or 125 small woad plants with a yield of 25 kg of fresh woad leaf to produce 50 g of woad powder, which could be enough to dye 1 kg of wool yarn mid-blue. At a less productive level, it could take as many as 286 large or 1,000 small plants with a yield of 200 kg of fresh woad leaf to produce 100 g woad powder to dye 1 kg wool yarn mid-blue (see an overview of results in fig. 9).

What is noteworthy in these results is the wide range of plant numbers required to dye yarns blue: a dyer could require as few as 36 large woad plants to dye 1 kg wool yarn blue, or as many as 1,000 small plants. There are many factors that underlie this variation, which may originate at any stage of the process; much depends on the skill of the dyer.

Woad blue textiles: accessible or exclusive?

Dyer's woad likes a rich, alkaline, soil, well drained for robust plant growth. To gain a plant rich in indigotin, the growing variables are considerable; they include the prevailing conditions at planting through to harvesting, the climate, the latitude, length of daylight and ultraviolet rays, the length of hot dry days prior to processing (Howard 2019, pers. corresp.). A cool summer can have such an adverse effect that there is only one annual harvest, with devastating results. In a good year, woad plants grow easily and have a high indigotin yield; in a poor year, the opposite is true. This raises the question as to whether dyer's woad was widely cultivated across the Mediterranean in the Early Iron Age. The agricultural economy of this period was likely in small fields close to settlements, some of which must have been dedicated to dyer's woad with the intent to obtain blue dyestuff. In addition, farmers of the first millennium BCE would have needed to resolve a depletion in soil fertility after growing woad. The risks and rewards of farming were no doubt an aspect of life in the agricultural communities of the early first millennium BCE. Assuming the availability of the raw materials (seed, soil, climate), agricultural knowledge and skills, this blue dye source could be regarded as accessible, yet unreliably so.

What was learnt from the experimental dye vats? The complexity in processing woad plants into dyestuff, and the chemistry of the woad dye vat, adds elements of risk to the dyeing process. There are three distinct dyeing techniques: direct dyeing, mordant dyeing and vat dyeing. Direct dyeing involves boiling or soaking suitable plants in water, creating a dye bath into which the material to be dyed is immersed (Cardon 2007, 4). Mordant dyeing requires an agent to bind the dye onto the fibre, such agents include alum (aluminium sulphate), iron and tannin. Vat dyeing, as required for woad and shellfish purple, is a more complex affair because the dyestuff is insoluble and must be reduced to its soluble form in alkaline conditions to be absorbed by the fibres (Cardon 2007, 4-5). Vat dyeing requires greater knowledge and skills than direct dyeing or mordant dyeing. This hints at the possibility of specialist and secret knowledge. Despite

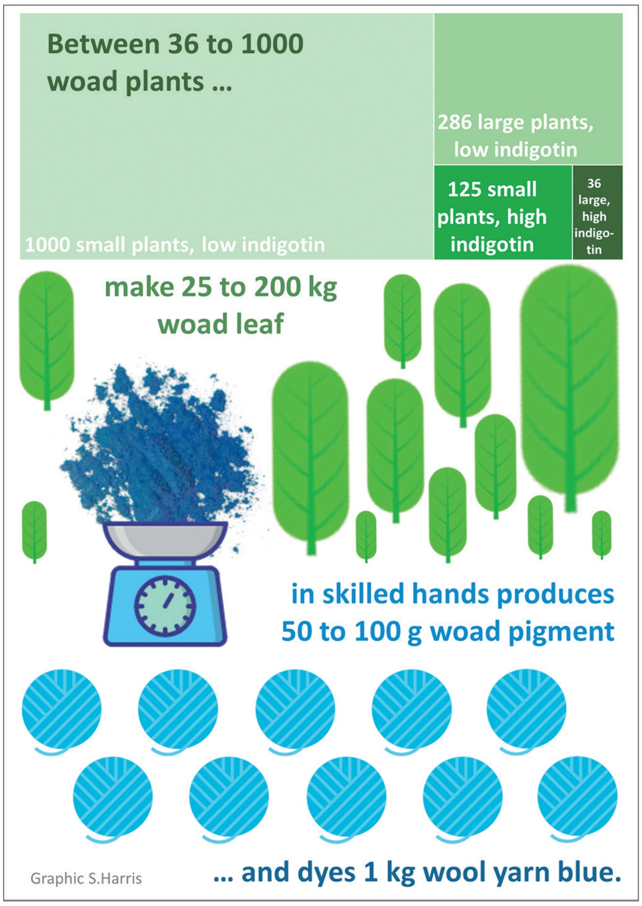


Fig. 9: Summary of results: how many woad plants does it take to dye 1 kg wool yarn blue? (Image: © Susanna Harris)

working with experienced dyers, the direct dyeing and urine dyeing in this experiment did not succeed. Woad dyeing is not predictable; there is always the possibility of shade differences or vat failure (see Hartl et al. 2015, 22-26). Encouragingly, once the dye vat is up and running, multiple dips or a richer dye solution (more dyestuff) can achieve a deep blue colour, until the vat is exhausted. It is well documented throughout history that woad dyeing is erratic. Repeating the same recipe under the same conditions will not guarantee success or the same shade of blue. Indeed, the historical and anthropological literature attests to the many mysteries surrounding indigotin extraction from a range of plants worldwide, and the resultant dye vats (Balfour-Paul 2011, 100, 119). In this way, the knowledge and resources needed to set up a woad dye vat and the skills and practices required to achieve blue textiles are less accessible than other dyeing methods, and the colour results are unpredictable. Thus, the skills to achieve blue dyed textiles may have been relatively exclusive.

At the beginning of this research, it was tempting to interpret the blue dyed textiles of the early first millennium BCE as relatively accessible. In suitable environments, the plant grows like a weed, and many contemporary home dyers report success dyeing with woad. During the progress of the research, it became apparent that these expectations are deceptive. Assuming the seeds became widely available across Europe in the first millennium BCE, dyer's woad was likely a relatively accessible raw material compared to shellfish purple. However, the unpredictability of the indigotin content in the plant, leading to the highly variable quantity of plants required to achieve blue textiles, plus the depletion of soils, makes this a somewhat unreliable crop. In addition, the specialist skills and intensive labour required in processing the plant into dyestuff, add to the unreliability of the dye vat in the hands of the inexperienced. It seems dyers today rarely report unsuccessful dye vats, giving a false sense of success. Indeed, two of the failed dye vats in this experiment are not reported here. Dye vats may, and do, fail in the sense that they do not result in blue dyed yarns (fibres or textiles). On the other hand, a successful dye vat is an asset to a dyer, who can prolong its life for months at a time, and use their skill to achieve a whole host of blue shades.

Dyers of the first millennium BCE skilled in the processes and knowledgeable about the techniques should expect repeated success, and with it the ability to produce various shades of blue, or indeed other colours. These all point to woad blue as a colour that was accessible to those with sufficient resources to counter the cumulative risks involved in obtaining it and the skills to carry out all stages of the process. Through this research it became apparent that woad blue dyed textiles were somewhat exclusive in terms of the plant resources and the complex skills required in processing the dye and creating a successful dye vat. A stripe or pattern of blue may have been an everyday luxury, to use the words of Lyn Foxhall (Foxhall 2005, 240), and available to many. By contrast, large dyed blue or indeed green (yellow/blue dye combination) textiles of the first millennium BCE may have been items of distinction. If this conclusion is correct, large quantities of blue or green textiles were part of the material culture of luxury, expense and exclusivity that characterised the life of early urbanites, aspiring elites, and wealthy communities of this period.

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