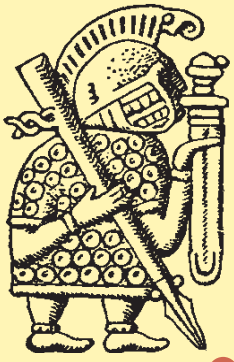

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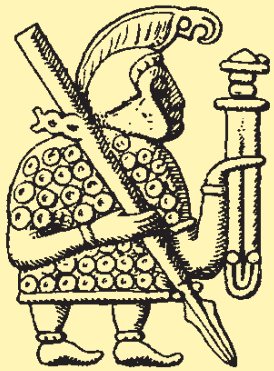

2025/4

First strontium isotope analysis of a heritage hemp fabric in Iceland

By Git Skoglund and Carlo Monti

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The strontium (Sr) stable isotope ratio ($^{87}Sr/^{86}Sr$) is a powerful hydrogeological and biogeochemical tracer and has been used to determine the geographical provenance of minerals and bones, as well as protein and plant fibers, but few textiles made of bast fibers. Here we report a first attempt to investigate the possibility of using Sr isotopic analysis to trace the origin of a heritage hemp (*Cannabis sativa*) fabric from Iceland likely made in the early 17th century and previously identified botanically. Iceland has a uniform young soil type formed by volcanic activity making it possible to collect a single soil sample and compare it to a reference sample of recently grown Icelandic hemp fibers. This special circumstance makes the Sr isotope ratio conclusive for determining whether the heritage textile hemp fibers were grown there or not. Fibers from a Romanian hemp towel were also analyzed as additional reference material, to calculate the sample size required when analyzing the Icelandic fabric. In total, four samples were analyzed, and the results are reported here. Strontium isotope signals indicate that hemp fibers from the Icelandic fabric were not grown on the island, and that they may have originated in France or Scotland.

Keywords: Linen, Hemp, *Cannabis*, Iceland, France, Scotland, Isotopes, Textile

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Introduction

Collections of the National Museum of Iceland in Reykjavik include much heritage needlework on plain bast fiber fabrics, and several examples have been found in churches. Most of them have also been analyzed in terms of embroidery design and patterns. Recently 13 fabrics were analyzed to ascertain which plants they are made of (Skoglund et al. 2024, p. 276). Several of them are woven of flax (*Linum usitatissimum*) yarns, three of them contained hemp yarns. One of those (accession number 1727) is a long wall-hanging, found in Thingeyrar church, located on the northern part of the island (fig. 1). This textile needlework in wool on a characteristically rustic homespun hemp fabric, according to the museum, it was locally made during the early 17th century. Its interpretation is based partly on embroidered personal names and a partial text taken from a hymn book which the Icelandic bishop Guðbrandur Þorláksson published at the end of the 16th century (www.sarpur.is/Adfang.aspx?AdfangID=326382, Accessed 7 December 2024). However, we do not know when the heritage hemp fabric was manufactured because it is impossible to determine the origin or era when a fabric was made simply from the embroidery,

Fig. 1. Wall-hanging, accession number 1727, likely made in the early 17th century. Wool-needlework on hemp ground, from Thingeyrar church. Size: 133 x 57.5 centimeters. Thread counts in warp and weft 13–14 threads per centimeter. Published with permission by National Museum of Iceland in Reykjavik.

and it may have been woven before the 17th century. Plain plant fabrics look much the same regardless of where or when they were made, but can in some cases be distinguished by the woven patterns corresponding with wall hangings of hemp or flax from other parts of Scandinavia (Skoglund et al. 2013; Skoglund 2016).

In Iceland during the early Middle Ages and later, fabrics made of bast fibers were called *lerépt* or *lerréptdukum* and were among tax revenues distributed to the many priests on the island. But it is problematic to ascertain whether these fabrics were made of locally grown fiber plants since there are few indications of local cultivation. There is only a single find of flax pollen from Iceland's Middle Ages. Secondly, place names with the prefix *lin* (literally flax), for example *Linakradalur* (flax field valley) or *Lineyjar* (flax islands) have previously been misinterpreted as places where flax cultivation took place (Larsson et al. 2012, p. 77). However, from the Icelandic Middle Ages until modern times *lin* was not the correct Icelandic word to denote flax, rather the Scandinavian term *hør* was used (Strömberg et al. 1974, p. 49). In parts of Scandinavia, the word *lin* was also used to denote other bast fiber plants such as hemp or hops (*Humulus lupulus*) (Ólavius 1770, pp. 67–73; Schøning 1910, pp. 13–14; Smidtnielsen 1926, p. 4). Moreover, in Finland the related term *liina*, originating from *linteum* (cloth), denoted nettles, flax, or hemp (Suomela et al. 2018, pp. 412–413). Therefore, based on terminology, hemp as well as other textile plants could have been grown in locations with the prefix *lin*. In addition, there is an archeological find of textile tools for the preparation of bast fibers (Larsson et al. 2012, p. 77) indicating that bast fiber processing was underway, but the raw fibers could have been imported. Finally, two written sources tell us that both hemp and flax were cultivated during the 18th century, and that hemp was grown on the western side of Iceland (Ólavius 1770, pp. 67–73; Smidtnielsen 1926, p. 10).

Apart from these observations, there is no empirical evidence that textile plants were cultivated in Iceland. The lack of additional written sources and archaeobotanical finds of pollen, seeds or fibers reveal a knowledge gap concerning Icelandic textile culture, as well as household resources and agriculture. Against this partially informative background, strontium (Sr) isotope analysis could be an important tool to increase our knowledge, and the heritage hemp fabric (accession number 1727) was selected as a first attempt. This item was chosen because the fabric

is damaged, and it has several holes with associated threads protruding from around the edges, which made it possible to sample a relatively large number of hemp fibers without further damaging the fabric.

Previous strontium isotope analyses

The strontium (Sr) stable isotope ratio ($^{87}Sr/^{86}Sr$) is a powerful hydrogeological and biogeochemical tracer and has been used to determine the geographical provenance of, for example, wine (Almeida & Vasconcelos 2001; Durante et al. 2013; Durante et al. 2015; Marchionni et al. 2013; Vinciguerra et al. 2016) and rice (Kawasaki et al. 2002; Ariyama et al. 2012; Lagad et al. 2017), as well as different vegetables (Bong et al. 2012, Di Giacomo et al. 2007; Trincherini et al. 2014; Monti et al. 2023). This analysis method was developed based on the assumption that $^{87}Sr/^{86}Sr$ ratios in surface water and soil-water depend on the geology of the watershed rocks and bedrocks, or both, and that the soil-water and surface water are the sources of bioavailable Sr. If so, the $^{87}Sr/^{86}Sr$ ratios in water are reflected in the $^{87}Sr/^{86}Sr$ ratios in organisms that take up this water. Baseline strontium isotope ratios for Iceland, estimated on the age and composition of the basalt, suggest a value of 0.703 to 0.704. Measured ratios on geological formations at different locations in Iceland confirm this value as the best estimate for the island (Schilling 1973; Wood et al. 1979; Dickin 1997; Taylor et al. 1998).

Strontium isotope analysis was previously employed to establish that wool in Icelandic heritage textiles came from sheep living on the island (Smith et al. 2019). But this technique had not been used to analyze plant textiles. In archaeology, strontium isotope analysis plays a vital role in reconstructing geographic origins and mobility, but its application differs significantly between plant- and animal-derived samples. For plant materials, the strontium isotopic signature ($^{87/86}Sr$) directly reflects the local bioavailable strontium from soil and water, making it a reliable indicator of the specific geological environment where the plant grew. In contrast, animal remains, especially bones, teeth or animal keratin fibres reflect a more complex integration of dietary inputs, which can include plants, water, and other animals from various sources. This means that while plant-based strontium data often provide a precise, localized signal, animal-based data may represent averaged or mixed signatures depending on the animal's range, dietary habits, and physiological factors. Consequently, interpreting strontium isotope ratios in animal remains requires careful consideration of trophic level, feeding behaviour and mobility, whereas plant isotopes typically offer a more direct reflection of a fixed location (Price et al. 2002).

To assign an origin to a plant sample based on its Sr isotope composition, the isotope ratio of the sample must be compared to data from authenticated samples from the region in question, because it cannot be certain that previous collected samples represent the full area. This issue is especially relevant for products from remote areas for which data from authentic reference samples are lacking or unobtainable. To evaluate the results, a prediction should be based on thorough knowledge of the geological and pedological characteristics of the soil, including its type and composition for the region (Capo et al. 1998) by analyzing its surface waters for an $^{87}Sr/^{86}Sr$ ratio (Voerkelius et al. 2010). In addition, the variability of $^{87}Sr/^{86}Sr$ ratios in soils is dependent on the origin and age of the bedrock the weathering of which has generated them (Capo et al. 1998). In young soils generated by the weathering of basalts or by direct sinking of dusts generated by volcanic activities, the $^{87}Sr/^{86}Sr$ values are in the range of 0.703 to 0.704 (Cole et al. 2022). As basalts represent about 80 percent of Icelandic bedrocks, the expectation is that the $^{87}Sr/^{86}Sr$ ratio of the soils, even if they receive saltwater aerosols or rainwater, will be less than 0.7065. This threshold is expected to be sufficient to distinguish between an Icelandic soil or plant grown on these soils, compared to other European soils or plants.

The confidence level of the results of analyzed Sr isotopic materials is dependent on the concentration of strontium in the fibers, multiplied by the weight of the sample. According to the literature, the concentration of strontium in hemp stalks is approximately 100 ppm (mg/kg) (Zafeiraki et al. 2021; Kaminski et al. 2024). For this reason, only a few milligrams of fibers should be sufficient to perform an analysis with low associated error. However, since no previous analyses have been reported on hemp fibers or other plant fibers from Iceland, it is necessary to first collect reference soil samples and validate this assumption by analyzing recently grown and dried hemp fibers. Based on those references, the laboratory can make an estimate of the Sr isotope footprints. But to additionally define our protocol and further specify the weight of fibers needed for a conclusive result, we added reference fibers from a Romanian hemp towel.

Methodology

The scope of this study is to determine whether the $^{87}Sr/^{86}Sr$ ratio found in Icelandic soils and hemp fibers recently grown in Iceland can be used to establish the expected $^{87}Sr/^{86}Sr$ values for Icelandic samples, and to test our hypothesis that the hemp fibers in the heritage textile came from hemp plants grown in Iceland.

Soil and hemp fiber samples were collected by the first author in the spring of 2023. A 250-gram soil sample was collected from a farm field on the southwest coast of Iceland at 5 to 10 centimeters below the soil surface using a sterile spade, placed in a sterile plastic 250 ml jar (model HDPE Aexit) and stored in an insulated cool bag. A total of 35 grams of dry hemp fiber was collected for a reference sample from plants grown the previous year on soil near the soil sampling site and placed in a sterile plastic zip bag. A 100-gram reference hemp fabric sample was collected in 2009 by the first author in Transylvania, Romania and was likely woven in the mid-20th century. It is made of a simple fabric woven in tabby, a common quality from the countryside in Europe. Botanical identity of the Romanian hemp fibers was verified using the manual Herzog test as described by Skoglund (2022, pp. 5–7). All three reference samples were sent in August 2023 to the Advanced Isotopic Analysis (AIA) laboratory in Pau, France. The Sr isotopic analysis results analyzed and compiled by the second author showed that two samples of only 10 mg each are required to give a conclusive Sr isotope result. With that information, the final fiber sampling was made on the heritage hemp fabric accession number 1727 by the first author in 2024, with the assistance of a conservator at the National Museum of Iceland. The fiber samples were taken from six different damaged parts of the fabric, which also minimizes the risk of any sample being contaminated.

Chemical analysis of the samples

In this Sr isotopic analysis project there are a total four samples and all have been analyzed (table 3). The first is of subsurface soil, the sec-

ond is of hemp fibers from plants recently grown on the same soil, the third consists of hemp fibers collected from the Romanian towel, and the fourth is of hemp fibers removed from the heritage hemp fabric accession number 1727 from Iceland.

As often $^{87}Sr/^{86}Sr$ value alone is not enough for a precise and univocal geographic origin determination of a plant, the elemental composition of the samples under study is used for further comparison (Monti et al. 2023). All four samples including leachate from the soil sample were analyzed, for lithium (Li), boron (B), sodium (Na), magnesium (Mg), aluminum (Al), potassium (K), calcium (Ca), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), copper (Cu), zinc (Zn), arsenic (As), bromine (Br), rubidium (Rb), strontium (Sr), molybdenum (Mo), silver (Ag), cadmium (Cd), barium (Ba), calcium (Ca), titanium (Ti), lead (Pb), uranium (U) and rare earth element contents, as well as their $^{87}Sr/^{86}Sr$ isotope ratios. All chemical analyses were conducted by Advanced Isotopic Analysis (AIA).

Elements concentration analysis

Also, rare earth elements (REE), coupled with advanced statistical methods, are a promising tool for the detection of the geographic origin of plants (Zhao & Yang 2019; Barbera et al. 2022). For this reason, total element concentration and rare earth element analyses were performed on a quadrupole ICP-MS (PlasmaQuant MS Elite, Analytik) after acid digestion of samples on a hot plate (Evapoclean, Analab). Fiber samples were mineralized in a mixture of HNO_3/H_2O_2 (5:1) and the soil sample with a mixture of HNO_3/HF (7:1). Samples were heated at 90°C for 24 hours. To control the quality of the mineralization step, two certified reference materials were analyzed under the same conditions as the samples (Tobacco leaves INCT-OBTL-5 and San Joaquin Valley soil NIST 2709a).

Strontium isotope analyses

Strontium isotopic $^{87}Sr/^{86}Sr$ analyses were performed on a multi-collector ICP-MS (MC-ICP-MS, Nu Plasma, Nu Instrument) using a sample-standard bracketing (SSB) approach. Prior to isotopic measurements, samples were purified with an ion-exchange resin (Sr-Spec, Triskem) after acid extraction. For the soil sample, Sr was extracted with ammonium acetate (1M, pH=7) to measure the isotopic composition of the Sr exchangeable fraction (Nasr 2022, p. 144). Quality control of the analyses was conducted using an isotopically certified standard (NIST 987, $SrCO_3$, USA). In addition, two certified reference materials (NIES 23, tea leaves and NIST 2709a, San Joaquin soil) with a known $^{87}Sr/^{86}Sr$ ratio were analyzed under the same conditions as the samples.

Results

Because rare earth elements (REE), coupled with advanced statistical methods, are a promising tool for the detection of the geographic origin of plants, for further research we also report the values here (Zhao & Young 2019; Barbera et al. 2022). Element content was analyzed in the Icelandic soil sample and recently grown hemp fibers, as well as the hemp fibers from the towel from Romania. The concentrations detected in those samples are reported in table 1. The composition of the two hemp fiber samples is different, the Icelandic recently grown fiber composition is dominated by K at 49.5% of total element content followed by Ca at 36.9%, while the Romanian fiber composition is dominated by Ca at 72.7% followed by Na at 7.9%. The percentage of all other elements analyzed is low compared with the prominent elements. The composition of the Icelandic soil is dominated by Fe at 81.4% followed by Ca at 14.9%. The concentrations of Sr are, respectively, 64.6 mg/kg for the recently grown Icelandic fiber sample, and 64.3 mg/kg for the Romanian fiber sample, Sr was not detected in the Icelandic soil leachate.

The composition of rare earth elements of the three samples analyzed is reported in table 2. The rare earth element composition of the two fiber samples is similar. Lanthanum (La) is the most abundant rare earth element in the Icelandic-grown hemp fiber sample accounting about the 34.0% followed by cerium (Ce) with 31.2% of the total. In the Romanian fiber sample, the most representative element is Ce with 40.3% followed by La with 21.2%. While the concen-

Table 1. Elemental compositions of the three samples studied measured in mg/kg with standard deviations (SD).

		F036ETC-1 Hemp fibers from Iceland		F036ETC-2 Hemp fabric from Romania		F036ETC-3 Soil from Iceland	
Element	**Unit**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Li	µg/kg-1	<0.050		<0.050		0.93	±0.08
B	µg/kg-1	8.70	±0.35	2.81	±0.11	38.2	±3.6
Na	µg/kg-1	656	±26	420	±17	N/A	
Mg	µg/kg-1	915	±37	321	±13	N/A	
Al	µg/kg-1	25.2	±1.0	178	±7	N/A	
K	µg/kg-1	6500	±260	91	±4	9632	±407
Ca	µg/kg-1	4847	±194	3860	±154	N/A	
V	µg/kg-1	0.296	±0.012	0.254	±0.010	430	±37
Cr	µg/kg-1	0.18	±0.01	1.79	±0.07	35.9	±2.7
Mn	µg/kg-1	33.2	±1.3	24.6	±1.0	1563	±99
Fe	µg/kg-1	63.0	±2.5	233	±9	52456	±2035
Co	µg/kg-1	0.046	±0.002	0.087	±0.003	45.8	±2.3
Cu	µg/kg-1	2.59	±0.10	3.53	±0.14	54.9	±3.6
Zn	µg/kg-1	10.5	±0.4	87.5	±3.5	176	±6
As	µg/kg-1	0.013	±0.001	0.054	±0.002	1.9	±0.1
Br	µg/kg-1	2.61	±0.10	0.280	±0.011	7.6	±0.7
Rb	µg/kg-1	3.85	±0.15	0.31	±0.01	N/A	
Sr	µg/kg-1	64.6	±2.6	64.3	±2.6	N/A	
Mo	µg/kg-1	0.065	±0.003	0.023	±0.001	1.54	±0.05
Ag	µg/kg-1	0.0072	±0.0003	0.078	±0.003	0.309	±0.013
Cd	µg/kg-1	0.0046	±0.0002	0.120	±0.005	0.204	±0.016
Ba	µg/kg-1	1.67	±0.07	12.1	±0.5	N/A	
Cs	µg/kg-1	0.0016	±0.0001	0.031	±0.001	N/A	
Ti	µg/kg-1	0.007	±0.000	0.003	±0.000	0.003	±0.000
Pb	µg/kg-1	0.036	±0.001	4.82	±0.19	4.8	±0.5
U	µg/kg-1	0.00100	±0.00004	0.141	±0.006	1.05	±0.03

Table 2. Rare earth element compositions of the three samples studied measured in µg/kg with standard deviations (SD).

		Hemp fibers from Iceland		Hemp fabric from Romania		Soil from Iceland	
Element	**Unit**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
La	µg/kg	129	±20	140	±11	15089	±766
Ce	µg/kg	117	±6	266	±17	40298	±1596
Pr	µg/kg	15.8	±1.0	31.2	±1.7	4547	±226
Nd	µg/kg	59.4	±3.6	119	±7	19035	±1064
Sm	µg/kg	11.5	±0.5	23.6	±0.5	3925	±293
Eu	µg/kg	3.3	±0.1	7.04	±0.42	1168	±99
Gd	µg/kg	14.2	±0.8	24.6	±0.8	3512	±274
Tb	µg/kg	2.25	±0.14	3.79	±0.04	510	±43
Dy	µg/kg	10.1	±0.9	19.3	±0.4	2897	±158
Ho	µg/kg	1.99	±0.04	3.59	±0.06	518	±40
Er	µg/kg	4.92	±0.16	10.2	±0.4	1370	±120
Tm	µg/kg	0.666	±0.036	1.40	±0.07	162	±9
Yb	µg/kg	3.70	±0.30	8.54	±0.57	926	±84
Lu	µg/kg	0.585	±0.054	1.371	±0.001	128	±11

trations of the other elements in the Romanian sample are roughly two times those of the Icelandic samples, their relative composition percentages are nearly the same. In the Icelandic soil the most important element is Ce at 42.8% followed by neodymium (Nd) which accounts for 20.2% of the total rare earth element concentrations (table 2).

Strontium isotopic ratio

The strontium isotopic ratio $^{87}Sr/^{86}Sr$ of all four samples, Icelandic soil, recently grown hemp fibers, hemp fibers from Romania, and the heritage hemp fabric is reported in table 3. The $^{87}Sr/^{86}Sr$ ratio of the recently grown hemp fibers and the soil are very similar, confirming that Sr uptake from the soil via the roots does not significantly alter the $^{87}Sr/^{86}Sr$ ratio in the plant's fibers. The $^{87}Sr/^{86}Sr$ of the Romanian hemp fibers is higher than in both the Icelandic-grown fibers and the soil sample. The value of $^{87}Sr/^{86}Sr$ of the heritage hemp textile is 0.70834, which is significantly higher than the $^{87}Sr/^{86}Sr$ values found for the Icelandic soil and locally grown hemp fibers.

Discussion

The $^{87}Sr/^{86}Sr$ ratio determined in the Icelandic soil and recently grown hemp fiber samples compared to the Romanian hemp fiber sample, indicates that $^{87}Sr/^{86}Sr$ value can be used to deter-

Table 3. $^{87}Sr/^{86}Sr$ ratios and standard deviations (based on analyses of three replicas of the same sample) as determined in the three samples analysed.

Sample source and location	Sample type	Geographic origin	$^{87}Sr/^{86}Sr$ ratio	Standard deviation
Arable soil	Soil	Iceland	0.70488	± 0.000050
Hemp grown on Icelandic soil	Hemp fibers	Iceland	0.70525	± 0.000050
Hemp towel	Hemp fibers	Romania	0.70817	± 0.000050
Heritage hemp fabric accession number 1727	Hemp fibers	Unknown	0.70834	± 0.000070

mine if the plant sample was grown on Icelandic soils. The value found on the Icelandic soils is typical of young soils recently formed due to volcanic activity, and it should match the $^{87}Sr/^{86}Sr$ values found in similar areas of the world where young soils were also formed through volcanic activities. A comparison of the values for the Icelandic soil and fiber samples to a distribution of the values in European soil samples (Voerkelius et al. 2010), confirms that the $^{87}Sr/^{86}Sr$ ratio is large enough that an Icelandic hemp plant sample cannot be confused with hemp plants grown elsewhere in Europe.

Our $^{87}Sr/^{86}Sr$ findings from the recently grown hemp fibers and soil are corroborated by ratios reported from geological formations at different locations throughout Iceland (Schilling 1973; Wood et al. 1979; Dickin 1997; Taylor et al. 1998), data gathered by an extensive study on Icelandic hydrochemistry (Cole et al. 2022), and research by Smith et al. (2019) who analyzed wool from a fabric found in a woman's burial site in Iceland.

Comparison of the data gathered in this study with previous research indicates that the differences in $^{87}Sr/^{86}Sr$ ratios between the Icelandic soils, soils from the Mediterranean Basin, and soils from the rest of Europe are sufficient to determine if the hemp fibers in the heritage fabric were grown in Iceland or not. Our results clearly show that the hemp fibers in this heritage fabric accession number 1727 were not grown on Icelandic soil, and comparison with other soil $^{87}Sr/^{86}Sr$ values (Bataille et al. 2018, p. 26) indicates that the most likely origin of the fibers in the heritage fabric is either Brittany or Normandy in France, or Scotland.

Conclusion

This project was a first attempt to investigate whether it is possible to use Sr isotopic analysis to determine the origin of a heritage hemp fabric accession number 1727 from Iceland. Our results show that the hemp fibers were not grown locally, and therefore this is the first demonstration of how the origin of historical hemp textile materials can be determined through Sr isotopic analysis.

In addition to previous research and literature used as a template when analyzing the Sr

isotopic results, our results are based on three important factors. First, the previous fiber analyses that identified the heritage fabric as hemp botanically, made it possible to collect a sample of recently grown Icelandic hemp fibers, and to analyze it to determine if there is a difference between the Sr value in hemp fibers compared to Icelandic soil. Our results show that the $^{87}Sr/^{86}Sr$ ratio of hemp fibers and soil are similar indicating that the uptake of Sr via the root of the plants does not significantly affect the ratio in the fibers. The second factor is that Iceland consists of a very young soil with an $^{87}Sr/^{86}Sr$ ratio between 0.703 and 0.704 that differs greatly from the Mediterranean Basin and the rest of Europe making it possible to exclude that the hemp fibers were grown in Iceland. The third factor was the Sr analysis of the hemp fabric from Romania which showed that only 10 mg of fibers is required for Sr isotope analysis, an important factor when sampling heritage textiles which are highly valued artefacts and should not be further damaged. For this reason, the National Museum of Iceland in Reykjavik gave us permission to sample the heritage textile.

Based on comparison with literature sources, we suggest that the geographical origin of the hemp fibers is either in France (Brittany or Normandy) or Scotland. However, we do not know if the raw fiber was imported to Iceland and processed into yarns and fabric locally, which could be the case since tools for bast fiber preparation were found in a burial site in Iceland. Nor do we know if the hemp fabric was woven in France or Scotland and exported to Iceland, to be used as the ground fabric for the needlework made locally. Still, it remains unclear whether textile hemp was grown historically in Iceland as indicated by old literary sources and prehistoric place names.

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