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There are few protocols available for DNA extraction from fungi. Here we present four complementary protocols for extraction of genomic DNA from fungi. We quantify the efficacy of extractions and compare eight species from five filamentous fungal genera, including both basidiomycetes and ascomycetes. These protocols should be useful for extraction of DNA from a variety of filamentous fungi.

Highlights

- Comparison of four DNA extraction protocols for fungi
- Freeze-drying greatly increases DNA yield
- CTAB extraction is optimal for high yield and fragment length
- Chelex is a quick technique for DNA extraction from fungi
Protocol
Orthogonal protocols for DNA extraction from filamentous fungi

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SUMMARY
There are few protocols available for DNA extraction from fungi. Here we present four complementary protocols for extraction of genomic DNA from fungi. We quantify the efficacy of extractions and compare eight species from five filamentous fungal genera, including both basidiomycetes and ascomycetes. These protocols should be useful for extraction of DNA from a variety of filamentous fungi. For complete details on the use and execution of this protocol, please refer to Conlon et al. (2021).

BEFORE YOU BEGIN
The protocols below describe 4 different DNA extractions performed for fungi. Our extractions used fungi grown in vitro on solid media, but extractions from liquid media should also be possible. For Protocols 1 and 2 there was an optional freeze-drying step. Protocol 3 is based on Walsh et al. (1991) while Protocol 4 is based on Suenaga and Nakamura (2005). In addition to comparing effectiveness between protocols, we also quantify the benefit of freeze-drying for DNA yield. All necessary reagents should be prepared in advance. For the CTAB protocol, isopropanol should be stored at –20°C.

The protocols in order are:

Protocol 1: CTAB (hexadecyltrimethylammonium bromide)
Protocol 2: Qiagen (Germany) DNeasy plant pro mini kit
Protocol 3: Chelex
Protocol 4: Chelex with proteinase K

Harvesting of fungal tissue

© Timing: 5 min

1. Weigh an empty 1.5 mL microcentrifuge tube.
   a. Record weight to allow calculation of starting weight.
2. Using a sterile scalpel, scrape ~50 mg (CTAB and Qiagen) or ~10 mg of mycelium from agar.
   a. In our extractions, starting weights varied from 30–75 mg (CTAB and Qiagen) and 5–11 mg (Chelex).
3. Place mycelium into the tube and weigh the full tube.
   a. Subtract empty weight from full weight to calculate starting material.
4. Store sample at −20°C.

**Freeze-drying of fungal samples**

- **Timing:** 12+ h

The freeze-drying process is the removal of ice or other frozen solvents from a material through the process of sublimation and consists of three stages: freezing, vacuum, and then drying. This step reduces DNA fragmentation and increases the quantity of DNA.

5. Completely freeze the tissue.
   a. This is achieved either by using liquid nitrogen or by storing in at -20 for 2–3 h.
6. Tubes are sealed with parafilm and 3–5 small holes are made in the lid using a needle.
   a. Parafilm ensures that the caps do not snap open during the freeze-drying process.
7. Store samples at −20°C.
8. Run the samples through the freeze-drying process using a freeze-dryer.
   a. For our samples, the vacuum was set to 0.018 mbar and temperature to −58°C.
9. Samples can be stored in a sealed container at 18°C–27°C for up to 1 year.

**KEY RESOURCES TABLE**

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| **Biological samples** |        |            |
| Leucoagaricus gongyliphorus | Acromyrmex echinatior ant colony (Panama) | Ae420B (420) |
| Leucoagaricus gongyliphorus | Acromyrmex echinatior ant colony (Panama) | Ae360 (360) |
| Termitomyces sp. | Macrotermes bellicosus termite colony (Ivory Coast) | IC0027 (27) |
| Termitomyces sp. | Macrotermes bellicosus termite colony (Ivory Coast) | IC0010 (10) |
| Podaxis carcinomalis | Trinervitermes sp. mound (Australia) | AQ 795752 (F) |
| Pseudoxyllaria sp. | Macrotermes natalensis termite colony (South Africa) | X802 (X) |
| Pseudoxyllaria sp. | Odontotermes sp. termite colony (Ivory Coast) | IC0057 (X57) |
| Escovopsis sp. | Paratrachymyrmex ant colony (Panama) | Escovopsis 176705 (E) |
| **Chemicals, peptides, and recombinant proteins** |        |            |
| Chelex 100 | Sigma-Aldrich, USA | Cat# C7901 |
| Protease K | QIAGEN, DE | Cat# 19131 |
| CTAB | Sigma-Aldrich, USA | Cat# H6269 |
| Tris | Merck, USA | Cat# GE17-1321-01 |
| NaCl | VWR, USA | Cat# 27810.295 |
| EDTA | Sigma-Aldrich, USA | Cat# 03685 |
| RNase A | QIAGEN, DE | Cat# 195939 |
| β-Mercaptoethanol | Sigma-Aldrich, USA | Cat# STBD6281V |
| Chloroform | Merck, USA | Cat# 1.02445 |
| Isoamyl alcohol | Merck, USA | Cat# 1.00979 |
| Phenol:Chloroform:Isoamyl alcohol | Fisher Scientific, USA | Cat# BP1752l |

(Continued on next page)
**MATERIALS AND EQUIPMENT**

### CTAB buffer

| Reagent            | Final concentration | Amount |
|--------------------|---------------------|--------|
| CTAB               | 2%                  | 20 g   |
| NaCl               | 1.4 M               | 82 g   |
| Tris               | 0.1 M               | 12.1 g |
| EDTA               | 20 mM               | 5.8    |
| ddH2O              | n/a                 |        |
| Total              |                     | 1 L    |

Adjust pH to 8 using HCl or NaOH and store at 18°C–27°C in a ventilated cupboard for up to one year.

**CRITICAL:** CTAB and EDTA should be handled with protective gloves in a fume hood.

### Chloroform: Isoamyl alcohol

| Reagent            | Final concentration | Amount   |
|--------------------|---------------------|----------|
| Chloroform         | 24                  | 48 mL    |
| Isoamyl alcohol    | 1                   | 2 mL     |
| **Total**          | **24:1**            | **50 mL**|

Store at 18°C–27°C in a ventilated cupboard for up to one year.

**CRITICAL:** Chloroform and isoamyl alcohol should be handled with protective gloves in a fume hood.

### 5M NaCl

| Reagent            | Final concentration | Amount |
|--------------------|---------------------|--------|
| NaCl               | 5M                  | 292.2 g |
| dd H2O             | n/a                 |        |
| **Total**          | 5M                  | 1 L    |

Store at 18°C–27°C for up to one year.
**STEP-BY-STEP METHOD DETAILS**

**Protocol 1: CTAB extraction for fungi**

© Timing: 7 h

The CTAB DNA extraction method is cheap, effective and applicable for a wide range of applications including DNA barcoding, shotgun sequencing and long-read sequencing. The protocol utilizes organic solvents and the harmful nature of some of the solvents, combined with the relatively long time to complete the protocol, can therefore be a limitation of using this method.

1. Harvest fungal material as outlined in *Before you begin* Steps 1-4.
2. Homogenize tissue
   a. Add 200 μL CTAB buffer to sample and grind tissue with a micropette.
      i. 1.5 mL Eppendorf tubes often work best
   b. Add 200 μL CTAB buffer to sample and grind tissue with a pipette tip with the end melted
      i. Place end of a 1000 μL pipette tip into the flame of an ethanol or Bunsen burner until the hole is sealed
      ii. Allow the tip to cool. The plastic end often becomes cloudy as it cools
   c. Homogenize using a Qiagen TissueLyser (or other lysis machine)
      i. Add glass beads or a heavy metal bead to the tube (2 mL Eppendorf tubes often work best for the heavy beads)
      ii. Run TissueLyser at 24 Hz for four min
3. Add 500 μL CTAB buffer, 7 μL Proteinase K, 7 μL RNase A and 7 μL β-Mercaptoethanol.
4. Incubate on a rotor at 65°C for at least 3 h (1 h if samples were freeze-dried).
5. Centrifuge for 5 min at 20,000×g.
6. Transfer supernatant to a new tube.
7. Add 700 µL phenol-chloroform-isoamyl alcohol (25:24:1).
8. Mix by turning upside down 100 times and incubate for 5 min at 18°C–27°C.
   a. Vortexing for 5 s is also possible but increases the risk of shearing DNA
9. Centrifuge for 30 min at 20,000×g and 20°C.
10. Transfer the upper phase, avoiding the white interphase, to a new tube.
11. Add 700 µL chloroform:isoamyl alcohol (24:1).
12. Mix by turning upside down 100 times and incubate for 5 min at 18°C–27°C.
   a. Vortexing for 5 s is also possible but increases the risk of shearing DNA
13. Centrifuge for 15 min at 20,000×g and 20°C.
14. Transfer upper phase, avoiding the white interphase, to a new tube while measuring supernatant volume.
15. Add 1/3 supernatant volume of 5M NaCl and 2/3 supernatant volume of ice-cold isopropanol to the tube.
   a. This step brings the DNA out of solution. While the isopropanol does not have to be ice-cold, it helps to improve overall yield.
16. Mix by turning upside down 20 times and centrifuge for 30 min at 20,000×g and 20°C.
17. Discard supernatants.
   a. Avoid disturbing any pellet with a pipette tip.
18. Add 750 µL 70% Ethanol and centrifuge for 3 min at 20,000×g.
   a. The use of ice-cold ethanol can improve yield.
   b. Can be repeated to increase purity.
19. Discard supernatants.
   a. Avoid disturbing any pellet with a pipette tip.
20. Air-dry pellets then add 50–100 µL EB buffer (or other elution buffer).
   a. Maximum time for air-drying is 10 min. Be sure to properly remove ethanol with a 10 µL pipette and the remaining ethanol will evaporate within a few minutes.
   b. Allow the sample to dissolve for at least 1 h at 18°C–27°C or for 12 h at 4°C.

**Note:** Unless otherwise indicated, centrifugation steps are at 18°C–27°C.

**Protocol 2: Qiagen DNeasy plant pro mini kit**

© Timing: 1 h 20 min

DNA extraction using the Qiagen (Germany) DNeasy plant pro mini kit. While more expensive than the other protocols, this kit is simple and relatively quick to use and is also available in a 96-well format.

21. Using starting material harvested according to Before you begin Steps 1-4, we followed the manufacturer’s instructions with the following options:
22. All centrifuge steps at 20°C.
23. Lysis using a Qiagen TissueLyser LT: 4 min at 24 Hz.
24. Step 5: addition of 250 µL Buffer CD2.

**Protocol 3: Chelex**

© Timing: 25 min

The Chelex extraction is cheap and very quick to extract from a lot of samples. The Chelex resin inhibits DNases which are not denatured by boiling. This protocol works very well for DNA barcoding and could potentially be used for shotgun sequencing. Extractions can be performed in a 96 well plate meaning it can be possible to extract DNA from 96 samples in under 1 h.
25. Place 5% Chelex solution on magnetic stirrer.
26. Following Before you begin Steps 1-4, harvest fungal mycelium into a 250 μL PCR tube.
27. Add 200 μL of 5% Chelex.
28. Vortex tubes for 15 s.
29. Incubate in a PCR machine at 99.9°C for 15 min.
30. Centrifuge tubes at 3,300×g for 3 min.
31. Transfer 100 μL of supernatant to a new tube.

Protocol 4: Chelex with proteinase K

© Timing: 40 min

This method is like the above Chelex protocol but with the addition of Proteinase K to assist lysis of the fungal cells and increase DNA yield.

32. Place 5% Chelex solution on magnetic stirrer.
33. Following Before you begin Steps 1-4, harvest 10–20 mg of fungal mycelium into a 250 μL PCR tube.
34. Add 200 μL of 5% Chelex with 20 mg/mL of Proteinase K.
35. Vortex tubes for 15 s.
36. Incubate in a PCR machine at 65°C for 30 min.
37. Centrifuge tubes at 3,300×g for 3 min.
38. Transfer 100 μL of supernatant to a new tube.

Agarose gel electrophoresis

© Timing: 120 min

We used agarose gel electrophoresis to provide a qualitative assessment of the length of DNA fragments in our extracts.

39. Pour 0.7%–1% (0.8% was used in this experiment) into a gel tray.
40. Mix 0.5 μL of 1 kb DNA Extension Ladder, 2 μL loading buffer and 2.5 μL H2O then add to the first well.
41. Mix 3 μL loading buffer with 2 μL sample DNA and add to individual wells.
42. Run gel at 60–70 V for approximately 90 min.

EXPECTED OUTCOMES

Based on our results, the protocols are expected to result in 30–60 ng DNA per mg of starting material for the CTAB and Chelex protocols and 6–8 ng DNA per mg starting material for DNeasy (Table 1). While freeze-drying did not have a significant effect on DNA yield (Figure 1A) or purity (Figures 1B and 1C), it did result in longer fragments, which would be suitable for long-read sequencing.

| Preparation | Extraction method | Time (h) | DNA yield per starting weight ng/mg | 260/280 | 260/230 |
|-------------|-------------------|---------|-----------------------------------|---------|---------|
| None        | Chelex            | 0.3     | 36.097 (8.454)                    | 2.064 (0.325) | 1.911 (1.213) |
| None        | Chelex with Proteinase K | 0.6     | 35.340 (7.359)                    | 1.439 (0.074) | 0.549 (0.045) |
| None        | CTAB              | 7       | 61.041 (18.885)                   | 1.979 (0.056) | 0.999 (0.174) |
| None        | DNeasy            | 1.25    | 7.566 (9.336)                     | 2.120 (0.255) | 0.586 (0.117) |
| Freeze-drying | CTAB            | 4       | 39.801 (16.996)                   | 2.019 (0.066) | 1.105 (0.181) |
| Freeze-drying | DNeasy         | 1.25    | 6.603 (2.861)                     | 1.711 (0.255) | 1.404 (0.540) |

Individual results available from Mendeley Data
Figure 1. Quantification of DNA extracts using Qubit and Nanodrop

(A) DNA yield per mg of starting material was highest for CTAB and Chelex extractions. However, both methods exhibited much more variation in yield than the DNeasy kit. White diamonds indicate mean values, thick black lines indicate median values, boxes correspond to the 1st and 3rd quartiles while whiskers correspond to the lowest value or 1.5 x the Interquartile Range (IQR), whichever is smallest.

(B) Protein and RNA contamination (quantified using 260/280 ratio) ratios were relatively consistent for all protocols. However, the readings for the DNeasy kit were much more variable than the CTAB and Chelex extractions. The addition of Proteinase K to the Chelex extraction appeared to increase the protein contamination. Dashed lines show the boundaries for an optimal value (1.7 and 1.9). White diamonds indicate mean values, thick black lines indicate median values, boxes correspond to the 1st and 3rd quartiles while whiskers correspond to the lowest value or 1.5 x the Interquartile Range (IQR), whichever is smallest.

(C) All extracts appeared to contain some reagent contamination (quantified using 260/230 ratio). While the results were consistent for most methods, the DNeasy protocol with optional freeze-drying exhibited much higher variation. Dashed lines show the boundaries for optimal values (1.8 and 2.2). White diamonds indicate mean values, thick black lines indicate median values, boxes correspond to the 1st and 3rd quartiles while whiskers correspond to the lowest value or 1.5 x the Interquartile Range (IQR), whichever is smallest.
The addition of Proteinase K to the Chelex extraction increased yield slightly (Figure 1A) and fragment length, meaning that this is potentially a good option for high-throughput DNA extraction for long-read sequencing. In order to represent the potential variability in yield and quality, as well as ease of replication, for each protocol, we performed each extraction once per strain.

**QUANTIFICATION AND STATISTICAL ANALYSIS**

DNA yield (ng/μL) was quantified using a Qubit 4 Fluorometer with a Broad Range dsDNA assay kit (Thermo-Fisher, USA). Protein and RNA contamination was assessed using a Nanodrop 1000 (Thermo-Fisher, USA) spectrophotometer by comparing the absorption ratio for $A_{260}$: $A_{280}$ ($260/280$) while reagent contamination was also assessed using the Nanodrop by comparing the absorption ratio for $A_{260}$: $A_{230}$ ($260/230$). DNA integrity and fragment size was assessed qualitatively using agarose gel electrophoresis (Table 1).

**LIMITATIONS**

The Chelex and DNeasy protocols are quick and result in enough DNA at a reasonable-enough purity for PCR or next-generation sequencing. However, the DNA fragment length was low for both protocols. The CTAB protocol results would therefore be preferable for long read sequencing and when DNA is extracted from limited amounts of starting material. CTAB has the added benefit of being more customizable than a kit. The Chelex protocol with the addition of Proteinase K appears to have produced relatively high concentrations of long-fragment DNA. This suggests that an added protein purification step could result in a quick, low-cost, and high-throughput method to extract DNA for long-read sequencing. We have, however, not attempted this here.

**TROUBLESHOOTING**

**Problem 1**

Incomplete phase separation in Steps 10 and 14 of CTAB extraction.

**Potential solution**

This can occur if the samples are not properly mixed before centrifugation, or if the samples are physically disturbed after centrifugation. In both cases, the solution is to mix and centrifuge the samples again.

(Figure 2). The addition of Proteinase K to the Chelex extraction increased yield slightly (Figure 1A) and fragment length, meaning that this is potentially a good option for high-throughput DNA extraction for long-read sequencing. In order to represent the potential variability in yield and quality, as well as ease of replication, for each protocol, we performed each extraction once per strain.

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**TROUBLESHOOTING**

**Problem 1**

Incomplete phase separation in Steps 10 and 14 of CTAB extraction.

**Potential solution**

This can occur if the samples are not properly mixed before centrifugation, or if the samples are physically disturbed after centrifugation. In both cases, the solution is to mix and centrifuge the samples again.
For Step 14, this could also be caused by the transfer of the incorrect phase from Step 10. It can therefore be advisable to retain the remaining liquid from Step 10 until after Step 14. The solution here would be to return to Step 9, otherwise it is necessary to restart the protocol with fresh material.

Problem 2
High protein content in CTAB extract.

Potential solution
This is often due to transferring some of the white interphase with the supernatant in Steps 10 and 14. It is therefore best to pipette slowly and to not to take all of the supernatant when performing these steps.

Problem 3
Low DNA yield.

Potential solution
If the yield is low but the quality of the sample is good, it would suggest that the starting sample amount could be insufficient or that cell lysis was unsuccessful. Cell lysis can be checked by placing the sample under a microscope. Increase the amount of starting material and repeat the extraction, change lysis method, Step 2 for CTAB protocol, or add a freeze-drying step to ensure enough DNA for downstream application.

Problem 4
260/280 ratio is outside optimal boundaries of 1.7 and 1.9. A value above 1.9 could indicate the presence of RNA in the extract, while a value below 1.7 could indicate the presence of protein or other organic tissues in the sample.

Potential solution
Process the starting material according to the recommended protocol instructions to ensure thorough removal of proteins. An important step is to not use too much starting material and to be sure not to transfer any of the white interphase in the CTAB protocol (see problem 2). To remove protein contaminants, it might be necessary to add protease or perform an additional phenol extraction step. In addition, ensure that wash steps are performed carefully to eliminate carryover of contaminants into the final sample.

Problem 5
260/230 ratio is outside optimal boundaries of 1.8 and 2.2. A value below 1.8 could indicate contamination with reagents.

Potential solution
Follow the recommendations for processing different sample types. Process the starting material according to the recommended protocol instructions. For the CTAB extraction, phenol or chloroform contamination can occur if the interphase is disturbed during Step 10 or 14. While a low 260/230 is not ideal, it is often possible to still use extracts in downstream applications; this was the case for several of the samples used for shotgun sequencing in Conlon et al. (2021).

Problem 6
Your downstream application is not working.

Potential solution
The quality of your genomic DNA is poor, potentially degraded, or there might be contaminants in your extract. Be sure to not start with too much starting material and ensure sufficient washing steps in your protocol (Step 18 in CTAB protocol). There might be residual ethanol remains in the sample.
when using ethanolic wash buffers for the final step in your DNA extraction. Be sure to thoroughly air dry the sample prior to adding the elution buffer. Use a 10 μL pipette to remove as much ethanol as possible before air drying.

Problem 7
Your DNA will not amplify in a PCR.

Potential solution
This can be due to the presence of PCR inhibitors in your extract. The addition of 0.004% Bovine Serum Albumin (BSA) to the PCR mix (0.1 μL for a 25 μL PCR) can help solve this.

RESOURCE AVAILABILITY
Lead contact
Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Benjamin H. Conlon (benjamin.conlon@bio.ku.dk).

Materials availability
There are no newly-generated materials associated with this protocol.

Data and code availability
Original data are available from Mendeley Data: https://doi.org/10.17632/683ybmk665.1

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AUTHOR CONTRIBUTIONS
Study designed by B.H.C. and S.S. with inputs from M.P. and J.Z.S. Experimental work carried out by B.H.C. and S.S. This first draft of the manuscript was written by B.H.C. and S.S. All authors contributed to the final manuscript.

DECLARATION OF INTERESTS
The authors declare no competing interests.

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