

# A First Assessment of the Conservation of the Mummified Human Remains in the Museo Egizio in Turin in the Framework of the "Mummy Conservation Project"

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The Museo Egizio in Turin holds a unique collection of 116 mummified or skeletal human bodies or body parts. This collection is currently under study by the "Mummy Conservation Project", a collaborative venture of the Museo Egizio, the Institute for Mummy Studies of Eurac Research, the Soprintendenza Archeologia del Piemonte, and the Horus Group, whose aim is to improve mummy conservation techniques. In the context of this project, an assessment of the state of preservation of the mummified human remains was carried out by monitoring basic physical parameters (temperature, relative humidity and water activity) and by performing a fungal survey. The latter revealed the presence on the mummified material of fungal spores and mycelia that could possibly pose a biodegradative threat. However, all the current physical parameters show that the mummies are stored under optimal environmental conditions, which will suppress any microbial up-growth.

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ملخص البحث: يحتوي المتحف المصري في تورينو على مجموعة فريدة تضم 116 قطعة ما بين مومياوات بشرية محنطة أو هياكل عظمية أو أجزاء بشرية محنطة. حالياً هذه المجموعة قيد الدراسة من قبل "مشروع الحفاظ على المومياوات"، هو مشروع تعاوني ما بين المتحف المصري ومعهد دراسات المومياوات بالأكاديمية الأوروبية للأبحاث (يوراك) ومكتب الحفاظ على التراث الأثري في مقاطعة بيمونتي ومجموعة حورس، التي تهدف إلى تحسين تقنيات الحفاظ على المومياوات. في نطاق هذا المشروع، تم تقييم حالة الحفظ للبقايا البشرية المحنطة من خلال مراقبة العوامل الفيزيائية الأساسية (درجة الحرارة والرطوبة النسبية ونشاط الجزيئات المائية) وإجراء مسح للفطريات. كشفت هذه الأخيرة عن وجود جراثيم وغزول فطرية على المواد المحنطة والتي يمكن أن تشكل تهديداً بالتحلل الحيوي. ومع ذلك تظهر جميع المقاييس الفيزيائية الحالية أن المومياوات يتم تخزينها في ظل ظروف بيئية مثالية، والتي سوف تثبط أي نمو للميكروبات.

## 1. Introduction

The first set of Egyptian mummies arrived in Turin following the scientific/commercial expedition undertaken by the traveler and naturalist, Vitaliano Donati, a professor of botany at the University of Turin, at the behest of King Charles Emmanuel III of Savoy between 1759 and 1762. In Egypt, Donati

collected some 1,689 scientific samples and objects,<sup>1</sup> including eighteen animal mummies. A second group of mummies, many probably coming from the ancient Egyptian capital city of Thebes (modern-day Luxor in southern Egypt), was collected by Bernardino Drovetti, Consul General of France to Egypt, and was bought, for the Turin collection,

by the Savoy king Charles Felix in 1824.<sup>2</sup> In 1888, when the two-volume catalogue of the Museo Egizio was completed by Ariodante Fabretti (1816-1894), Francesco Rossi (1827-1912) and Rodolfo Vittorio Lanzone (1834-1907), it included a total of twelve complete human mummies, nine heads – two of which were associated with a hand – two hands with rings, four pseudo-mummies, and seventy-eight animal mummies. The human mummies entered the collection inside wooden anthropoid coffins, and the inscriptions that grace these coffins specify the names and professions of the deceased they were meant for, supposedly the same people whose mummified bodies were contained in the coffins.<sup>3</sup> Finally, thanks to Ernesto Schiaparelli, director of the Museo Egizio between 1894 and 1928, the number of mummies in the collection was further increased. A buying trip to Egypt, done by Schiaparelli in 1900/1901, led to the purchase of more than 1,500 items, including two naturally mummified adult bodies and the mummy of a small child dating to about 3500 BCE. But it is especially since the foundation of the Italian Archaeological Mission to Egypt in 1903 that a large number of human remains was discovered at various sites along the Nile, during many excavation seasons directed by Egyptologists Ernesto Schiaparelli and, later on, Giulio Farina, who were assisted, since 1914, by anthropologist Giovanni Marro.<sup>4</sup> A total of 116 mummified or skeletal human bodies and body parts are recorded today in the Museum database as coming from these fieldwork campaigns, but 20 more mummies, 650 complete skeletons, and 144 skulls, presently held in the Turin Museum of Anthropology and Ethnography,<sup>5</sup> most likely also derive from the same excavations.

Given the increasing attention among researchers to the mummified human remains held in the Museo Egizio in Turin, in 2016 the “Mummy Conservation Project” was set up, with the aim of incorporating the data and knowledge acquired so far on these human remains in order to develop a protocol for proper museum conservation and display.

The goals of the “Mummy Conservation Project” illustrated in this paper were the following:

- Taking thermo-hygrometric measurements in the galleries, the inside of display cases, in the mum-

my storage room, and in the room where the research operations were carried out.

- Measuring the water activity (aw) of the mummies.
- Fungal spore sampling of the air in the galleries, inside a display case, in the mummy storage room, and in the room where the research operations were carried out.
- Fungal survey of the mummified material.

## 2. Research aim

In view of the Museo Egizio and Eurac Research’s common interest in developing know-how to help preserve all the Museo Egizio’s mummies – both those on display and those in storage – special emphasis was placed on testing water activity (aw), a parameter that affects the rate of biochemical decay in organic tissues. This important parameter is significantly affected by temperature and relative humidity in the conservation environment. In parallel to the assessment of this physical parameter, a first microbial survey was performed.

To identify the presence of possible superficial growing fungi, samples of both textiles and skin were taken using non-invasive contact plates.

To obtain further knowledge of the environmental conditions the mummies are presently experiencing, the researchers also took samples of spores present in the air inside the storage room where the mummies were kept, in a display case in the permanent galleries, and in the room where the research operations were carried out.

The aim of this work is to expand on research on the conservation organic objects of historical and artistic interest by assessing both biological and physical-chemical conservation requirements.

## 3. Material and methods

### 3.1 Thermo-hygrometric measurement of the exhibition areas, inside a display case, in the mummy storage room, and in the room where the research operations were carried out

Thanks to historical data relative to the thermo-hygrometric conditions of the museum’s exhibition spaces and the storage space where the mummies were kept (prior to the inauguration of the new galleries in 2015), it was possible to identify the sea-



**Fig. 1:** A phase of a non-invasive water activity (aw) test carried out on the mummy of Kha (Suppl. 8431). Picture by Eurac Research, Institute for Mummy Studies.

sonal trend these relics were subjected to.

With the exception of the room where the Tomb of Kha and Merit was display – where a wall-mounted air conditioner and a portable humidifier were installed – all the rest of the museum and storage lacked an air conditioning system. Climate monitoring took place in “sample” mode over different periods and in different areas of the museum with the aid of data loggers (HumiStick). The recorded temperature ranged between 21 °C and 30 °C, and the recorded relative humidity between 30 % and 66 %. In 2015, a new air conditioning system was installed, serving all the exhibition halls, the Foundation’s offices, and the storage spaces. It is powered by an underground thermo-cooling plant using geothermal energy.

To date, the museum’s different exhibition areas have depended on auxiliary machines whose temperature and relative humidity values can be individually and independently set.

### 3.2 Measuring water activity (aw) of the mummies

As regards this specific phase of the project, a total of 106 organic samples were analysed, both of a vegetal nature (bandage linen) and of human origin

(fragments of bone, skin, muscles, connective tissue, hair, Fig. 1).

To measure the water activity (aw) value, the Rotronic instrument, model HygroPalm HP-23-AW-A, was used. Prior to measuring the samples, the HC2-AW and the relative Rotronic HC2-SH measurement probe were calibrated as needed.

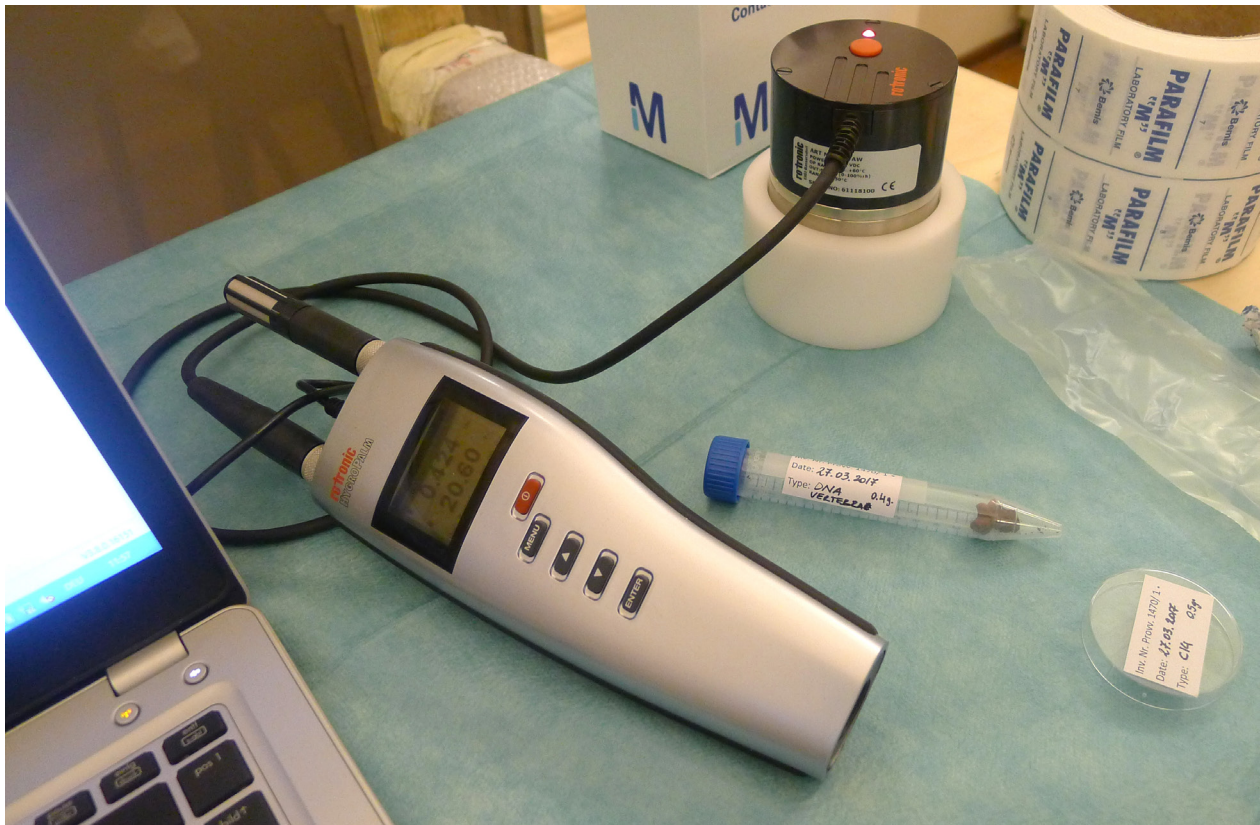
Immediately after sampling the mummified organic tissues, the water activity of the samples was examined. The samples were then placed inside special sample holders, previously sterilised. The Rotronic HW4 software version 3.8.0 was used to validate the measurements obtained. Once the PC was connected to the analyser, it was possible, through this application, to set the necessary operating settings in order to obtain the measurement (Fig. 2).

Simultaneously with the water activity (aw) acquisition phase, the temperature and relative humidity values of the environment were obtained. The time required to acquire each sample is approximately 5 minutes. At the end of each acquisition, a validation certificate was produced in form of a PDF file.

### 3.3 Sampling and cultivation of fungi

Non-invasive sampling using contact agar plates (DG18 and 2 % MEA, Merck) was performed as pre-





**Fig. 2:** Instrumental configuration for assessing water activity (aw). Picture by Marco Samadelli/Eurac Research, Institute for Mummy Studies.

viously described<sup>6</sup> on different materials for the cultivation of superficial growing fungi (Fig. 3). The samples were taken from different materials found in the mummies, including soft tissue and textile material. We generated data from 18 mummies from the museum's storage room "Ipogeo magazzino visitabile" and 6 mummies stored in display cases. Air-borne fungi were collected on DG18 and 2 % MEA plates using an air sampler (SAS) Super-90 (PBI International, Milan, Italy), with a sampling volume of 100 litres (Fig. 4). Fungi collected from the contact plates and air samples were purified by several transfers onto 2 % MEA and DG18 plates.

### 3.3.1 DNA extraction, PCR amplification and sequence analysis

Pure cultures were identified based on the sequencing of internal transcribed spacer region (ITSI-5.8S-ITSII), a sequence that can be used as a phylogenetic marker. DNA was extracted from the purified cultures using fresh mycelia, as described by Michaelsen et al.<sup>7</sup> For the analysis of fungal ITS sequences, we PCR amplified this genomic region

using specific ITS primers,<sup>8</sup> using the conditions described by Pinar et al.<sup>9</sup> To identify the fungi, we compared the obtained sequence material to fungi ITS sequences available in the online public database NCBI, using the BLAST search program.<sup>10</sup>

## 4. Results and discussion

### 4.1 Observations on the results of water activity (aw) analysis

Water activity analysis is a widely-used technique in food storage control.<sup>11</sup> Its application in the field of cultural heritage conservation, on mummified biological samples, is innovative and pioneering.

The importance of relative humidity (RH) to conservation is immense,<sup>12</sup> and closely linked to the concept of water activity (aw), the parameter proportional to the escaping tendency of the water molecules present in the tissues constituting the mummy. Water activity (aw) is calculated as the ratio of the partial vapour pressure of water in tissues (Pw) to that of pure water (Pw0) at the sample's surface temperature.<sup>13</sup>

After a certain time, any substance placed in a sealed

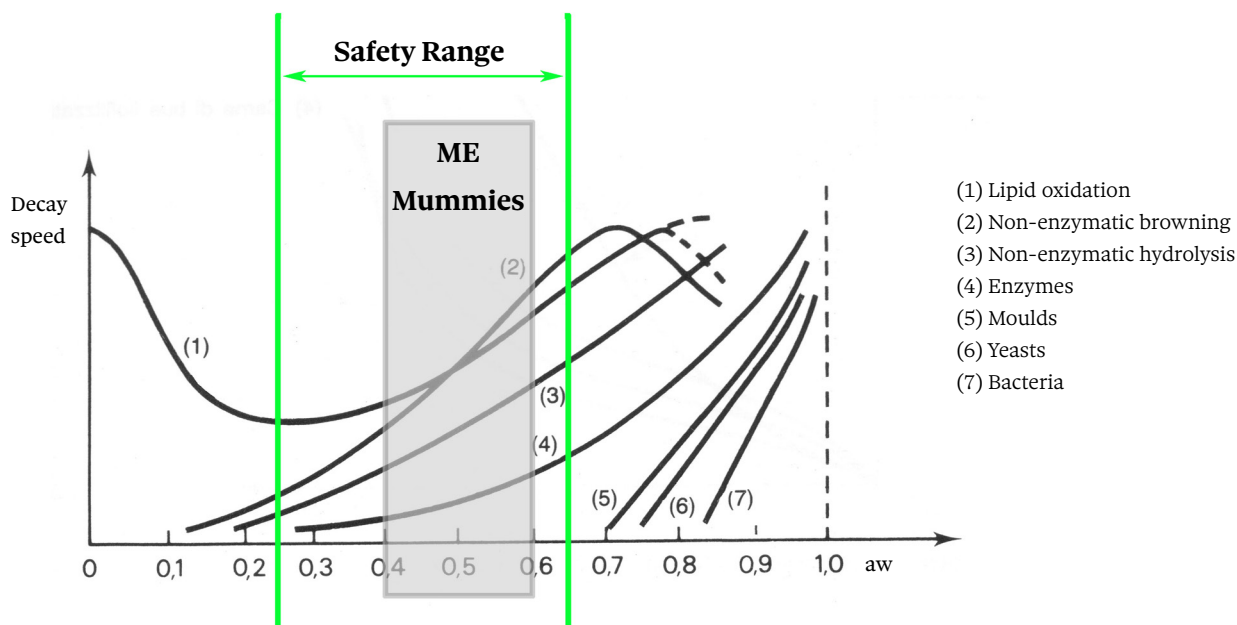




**Fig. 3:** Direct microbiological sampling on the surface of mummy Cat. 2245. Picture by Marco Samadelli/Eurac Research, Institute for Mummy Studies.



**Fig. 4:** Sampling of spores present in the air inside display cases (Suppl. 19691). Picture by Marco Samadelli/Eurac Research, Institute for Mummy Studies.



**Fig. 5:** Positioning of the results of water activity ( $a_w$ ) testing on the mummies in relation to the decay speed of organic tissues as a function of water activity ( $a_w$ ) [Labuza, T.P., 1975].

environment reaches a “thermal and hygrometric” equilibrium with the air surrounding it. Accordingly, the substance’s moisture content reaches an equilibrium with the humidity of the environment (EMC). Under these conditions, the value of the air’s equilibrium relative humidity (ERH) corresponds to the water activity ( $a_w$ ) value of the substance.<sup>14</sup>

From the chemical point of view, tissues constituting mummies can be considered as concentrated “solutions”, and measurement and limitation of water activity ( $a_w$ ) are essential to the conservation process because they influence the life of microorganisms and enzyme activity. The greater the water activity ( $a_w$ ) value, the faster the decay of organic tissue, as synthetically represented in the chart (Fig. 5).<sup>15</sup>

Relative humidity values higher than 65 %, combined with temperature values higher than 20 °C, promote the development of moulds and accelerate the metabolism of many harmful insects. It is scientifically demonstrated that, with water activity ( $a_w$ ) lower than 0.3, it is possible to inhibit the majority of the causes of biochemical decay in organic tissue.<sup>16</sup>

A total of 106 mummified samples were subjected to water activity ( $a_w$ ) tests. The results of the analysis are illustrated in Tables 1A and 1B (Tab. 1A and Tab. 1B).

The results of our water activity ( $a_w$ ) examination shows that most of the analysed mummies are in the

range between 0.4 and 0.5 ( $a_w$ ) (Fig. 6). No differences were noted, with respect to this type of analysis, between one mummy and the other, even when kept in different environments. This uniformity of results is not surprising, because the same homogeneity was observed in the climatic parameters of the museum’s exhibition environments and display cases, and of the mummy storage room.

In conclusion, observing the results of the water activity ( $a_w$ ) analysis on the mummified samples, reported in tables 1A and 1B (Tab. 1A and Tab. 1B), and comparing them with recent theoretical and experimental studies relative to the conservation of organic mummified finds,<sup>17</sup> it can be stated that:

1. the observed water activity levels are consistent with those expectable in the environmental climatic conditions provided by the museum,
2. the analysed mummies are preserved within the safety parameters provided for proper conservation, as they all remain within the ideal range between 0.25 – 0.65 ( $a_w$ ), as shown in Fig. 5.<sup>18</sup>

## 4.2 Microbiological analysis

Through the fungal survey applied in this study, we were able to detect and identify different fungal genera and species on skin and textile samples taken from mummies from both the storage rooms and the display cases (Fig. 7). Interestingly, the number of

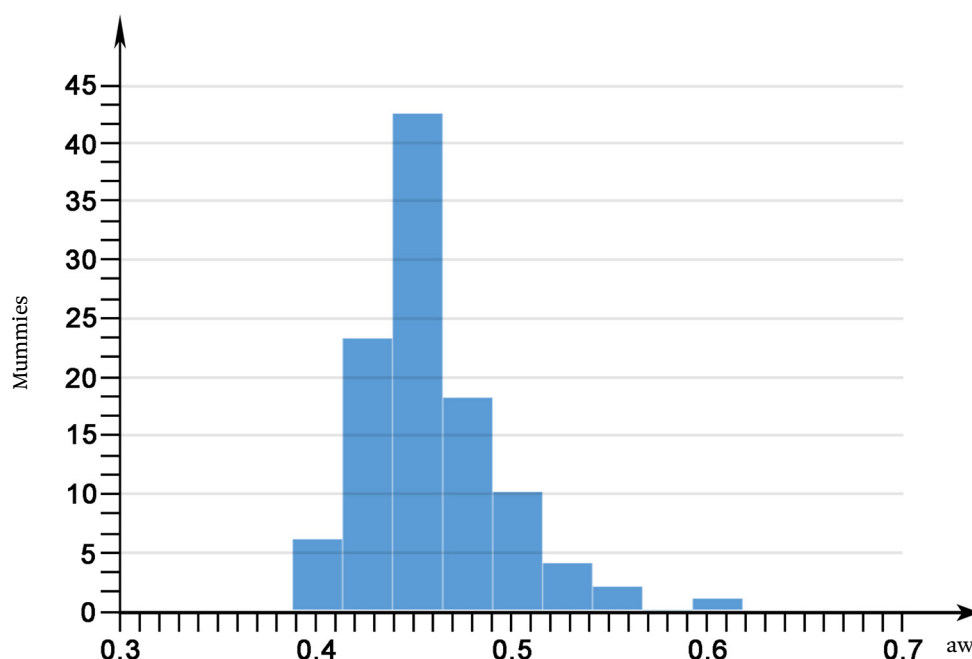


| Mummy (INV. N.) | Museum location   | Sampling date | Microbial survey |       | AW     | Taw (°C) |
|-----------------|---|---------------|------------------|-------|--------|----------|
|                 |   |               | MEA2%            | DG18  |        |          |
| Cat. 2211/2     | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 3         | 28/03/2017    | FS46             | FS45  | 0,4460 | 22,81    |
| Cat. 2213/ 2    | Ipogeo - magazzino visitabile - cassa 009                       | 31/03/2017    | -                | -     | 0,4580 | 22,53    |
| Cat. 2215/2     | Sala 11 vetrina 03  | 03/04/2017    | -                | -     | 0,4391 | 23,18    |
| Cat. 2218/2     | Sala 11 vetrina 03  | 03/04/2017    | FS95             | FS96  | 0,4530 | 23,09    |
| Cat. 2220/ 3    | Ipogeo - magazzino visitabile - scaffale 09 - ripiano 1         | 31/03/2017    | FS80             | FS79  | 0,4476 | 22,40    |
| Cat. 2223       | Ex-Antichità - cassa  | 05/04/2017    | -                | -     | 0,4170 | 24,65    |
| Cat. 2230/1     | Sala 13 vetrina 01  | 05/04/2017    | -                | -     | 0,4920 | 24,58    |
| Cat. 2231/02    | Sala 11 vetrina 03  | 03/04/2017    | -                | -     | 0,4530 | 22,77    |
| Cat. 2233       | Ex-Antichità - cassa  | 05/04/2017    | -                | -     | 0,4239 | 24,31    |
| Cat. 2245       | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 1         | 29/03/2017    | -                | -     | 0,4290 | 21,70    |
| Cat. 2253       | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 1         | 28/03/2017    | FS35             | FS36  | 0,4221 | 22,32    |
| Cat. 2254       | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 3         | 28/03/2017    | -                | -     | 0,4339 | 22,44    |
| Cat. 2256       | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 1         | 28/03/2017    | FS39             | FS40  | 0,4021 | 22,49    |
| Provv. 0549     | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 2         | 28/03/2017    | FS44             | FS43  | 0,4540 | 22,75    |
| Provv. 0578     | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 4         | 29/03/2017    | -                | -     | 0,4200 | 21,48    |
| Provv. 0610     | Ipogeo - magazzino visitabile - cassa + scaffale 14 - ripiano 1 | 31/03/2017    | -                | -     | 0,4460 | 22,10    |
| Provv. 0611     | Ipogeo - magazzino visitabile - scaffale 07 - ripiano 2         | 29/03/2017    | FS57             | FS58  | 0,4891 | 25,15    |
| Provv. 0612     | Ipogeo - magazzino visitabile - scaffale 07 - ripiano 1         | 30/03/2017    | FS70             | FS69  | 0,4605 | 22,33    |
| Provv. 0731     | Ipogeo - magazzino visitabile - scaffale 09 - ripiano 2         | 30/03/2017    | -                | -     | 0,4310 | 22,62    |
| Provv. 0996     | Sala 12 vetrina 06  | 27/03/2017    | FS21             | FS22  | 0,4060 | 22,07    |
| Provv. 1448     | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 4         | 30/03/2017    | -                | -     | 0,4231 | 20,81    |
| Provv. 1449     | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 2         | 29/03/2017    | FS53             | FS54  | 0,4620 | 22,75    |
| Provv. 1453     | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 1         | 29/03/2017    | -                | -     | 0,5005 | 22,87    |
| Provv. 1456     | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 3         | 28/03/2017    | FS48             | FS47  | 0,4102 | 22,77    |
| Provv. 1457     | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 4         | 29/03/2017    | -                | -     | 0,4411 | 20,40    |
| Provv. 1468     | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 1         | 29/03/2017    | FS55             | FS56  | 0,5512 | 24,42    |
| Provv. 1470/ 1  | Ipogeo - magazzino visitabile - scaffale 05 - ripiano 4         | 27/03/2017    | -                | -     | 0,4150 | 20,65    |
| Provv. 1471     | Ipogeo - magazzino visitabile - scaffale 07 - ripiano 3         | 29/03/2017    | -                | -     | 0,4722 | 25,56    |
| Provv. 1473     | Ipogeo - magazzino visitabile - cassa 007                       | 30/03/2017    | FS68             | FS67  | 0,4485 | 21,82    |
| Provv. 1475     | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 3         | 28/03/2017    | FS25             | FS26  | 0,4489 | 20,63    |
| Provv. 1478     | Ipogeo - magazzino visitabile - scaffale 09 - ripiano 2         | 30/03/2017    | FS74             | FS73  | 0,4591 | 22,75    |
| Provv. 1480     | Sala papiroteca - scaffale 12                                   | 03/04/2017    | -                | -     | 0,4611 | 21,06    |
| Provv. 1488/1   | Ipogeo - magazzino visitabile - scaffale 11 - scatola 06        | 05/04/2017    | -                | -     | 0,6185 | 22,44    |
| Provv. 1513/1   | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 2         | 28/03/2017    | -                | -     | 0,4310 | 20,03    |
| Provv. 4156/2   | Magazzino legni, scatola 021                                    | 04/04/2017    | -                | -     | 0,4520 | 22,83    |
| Provv. 4243/1   | Magazzino legni, scatola 080                                    | 01/04/2017    | -                | -     | 0,4762 | 22,35    |
| Provv. 4765/2   | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 4         | 06/04/2017    | -                | -     | 0,5170 | 22,55    |
| Provv. 5532     | Ipogeo - magazzino visitabile - scaffale 10                     | 03/04/2017    | -                | -     | 0,4611 | 20,62    |
| Provv. 5535     | Magazzino "legni "sabauda" scaffale Q 4                         | 05/04/2017    | -                | -     | 0,5216 | 23,28    |
| Provv. 6107     | Ipogeo - magazzino visitabile - scaffale 14 - ripiano 2         | 04/04/2017    | -                | -     | 0,4591 | 22,62    |
| Provv. 6108     | Ipogeo - magazzino visitabile - cassa 763                       | 05/04/2017    | -                | -     | 0,5152 | 23,14    |
| Provv. 6112     | Ipogeo - magazzino visitabile - cassa 759                       | 05/04/2017    | -                | -     | 0,5280 | 22,94    |
| Provv. 6126/7   | Ipogeo - magazzino visitabile - scaffale 4 - ripiano 3          | 06/04/2017    | -                | -     | 0,5561 | 22,92    |
| Provv. 8135     | Ipogeo - magazzino visitabile - scaffale 09 - ripiano 4         | 30/03/2017    | -                | -     | 0,4408 | 22,64    |
| Suppl. 00278    | Sala 15 vetrina 02  | 27/03/2017    | -                | -     | 0,4403 | 21,83    |
| Suppl. 00293    | Sala 02 vetrina 01  | 06/04/2017    | FS103            | FS104 | 0,4997 | 21,93    |
| Suppl. 00304    | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 3         | 29/03/2017    | -                | -     | 0,5662 | 23,88    |
| Suppl. 05050    | Sala 10 vetrina   | 27/03/2017    | FS15             | FS16  | 0,4431 | 21,92    |
| Suppl. 05066    | Sala 10 vetrina   | 27/03/2017    | FS12             | FS11  | 0,4540 | 21,77    |
| Suppl. 05109    | Magazzino "biblioteca", armadio A, ripiano 9                    | 03/04/2017    | -                | -     | 0,4490 | 22,56    |
| Suppl. 05142/2  | Magazzino "biblioteca", armadio A, ripiano 9                    | 03/04/2017    | -                | -     | 0,4231 | 22,21    |
| Suppl. 05147    | Magazzino "biblioteca", armadio A, ripiano 9                    | 03/04/2017    | -                | -     | 0,4110 | 21,76    |
| Suppl. 05154    | Magazzino restauro  | 01/04/2017    | -                | -     | 0,5029 | 22,54    |
| Suppl. 05226/2  | Sala 08 vetrina 09  | 27/03/2017    | -                | -     | 0,3791 | 21,70    |
| Suppl. 05227/2  | Sala 08 vetrina 08  | 27/03/2017    | FS14             | FS13  | 0,4231 | 21,74    |
| Suppl. 05270    | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 2         | 28/03/2017    | FS41             | FS42  | 0,4131 | 22,58    |
| Suppl. 05271    | Ipogeo - magazzino visitabile - scaffale 01 - ripiano 3         | 31/03/2017    | -                | -     | 0,4681 | 23,09    |
| Suppl. 07715/01 | Sala 08   | 05/04/2017    | -                | -     | 0,4745 | 22,91    |
| Suppl. 07716    | Sala 06 vetrina 07  | 05/04/2017    | -                | -     | 0,4906 | 23,56    |
| Suppl. 07717    | Soppalco - armadio 03 fibre vegetali - ripiano 3                | 04/04/2017    | -                | -     | 0,4673 | 22,77    |
| Suppl. 07718    | Magazzino legni, scatola 120                                    | 04/04/2017    | -                | -     | 0,4721 | 22,89    |
| Suppl. 07719    | Magazzino legni, scatola 117                                    | 03/04/2017    | -                | -     | 0,4511 | 22,87    |

**Tab. 1A:** The results of the water activity (aw) value for the mummies, correlated with the acquisition temperature value Taw (°C) of the room where the research operations were carried out.

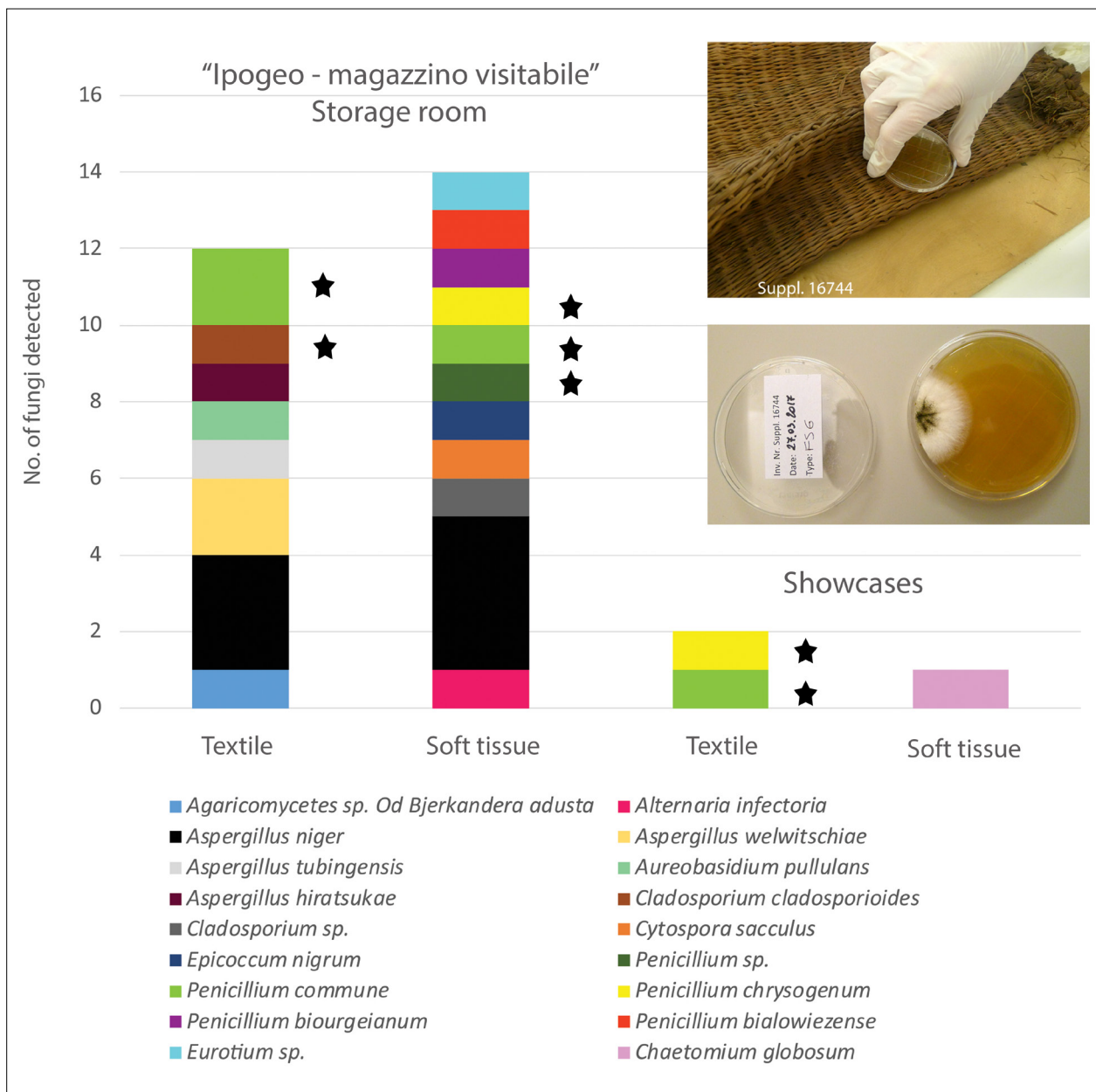
| Mummy (INV. N.)                 | Museum location   | Sampling date | Microbial survey |      | AW     | Taw (°C) |
|---------------------------------|---|---------------|------------------|------|--------|----------|
|                                 |   |               | MEA2%            | DG18 |        |          |
| Suppl. 08876/a                  | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 1 | 31/03/2017    | -                | -    | 0,4460 | 22,63    |
| Suppl. 08942                    | Ipogeo - magazzino visitabile - scaffale 13 - ripiano 4 | 31/03/2017    | -                | -    | 0,4425 | 22,55    |
| Suppl. 08943                    | Ipogeo - magazzino visitabile - scaffale 05 - ripiano 4 | 27/03/2017    | -                | -    | 0,4328 | 20,89    |
| Suppl. 08983/1                  | Magazzino legni, scatola 025                            | 04/04/2017    | -                | -    | 0,4320 | 22,55    |
| Suppl. 10534/3                  | Ipogeo - magazzino visitabile - scaffale 05 - ripiano 3 | 27/03/2017    | -                | -    | 0,4100 | 21,37    |
| Suppl. 11110                    | Ipogeo - magazzino visitabile - scaffale 04 - ripiano 4 | 28/03/2017    | -                | -    | 0,4550 | 22,70    |
| Suppl. 13086 (?)                | Ipogeo - magazzino visitabile - cassa 759               | 05/04/2017    | -                | -    | 0,5410 | 22,46    |
| Suppl. 13088                    | Sala 03 vetrina 05 IN                                   | 05/04/2017    | -                | -    | 0,5080 | 22,87    |
| Suppl. 13966/1                  | Sala 03 vetrina 02 TdI                                  | 03/04/2017    | -                | -    | 0,4231 | 22,93    |
| Suppl. 14061/2                  | Sala 02 vetrina 13                                      | 06/04/2017    | -                | -    | 0,4980 | 22,93    |
| Suppl. 14064/2 (?)              | Ipogeo - magazzino visitabile - cassa 008               | 01/04/2017    | -                | -    | 0,4690 | 21,71    |
| Suppl. 14067, ex Suppl. 15815   | Sala 02 vetrina 08                                      | 04/04/2017    | -                | -    | 0,4583 | 22,05    |
| Suppl. 14168/01                 | Magazzino vasi giallo, stanza 02, armadio 8, TOP        | 04/04/2017    | -                | -    | 0,4561 | 22,75    |
| Suppl. 14378/a                  | Sala 04 vetrina 07 (dentro sarcofago 14378)             | 03/04/2017    | -                | -    | 0,3951 | 23,21    |
| Suppl. 14381/1                  | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 3 | 30/03/2017    | -                | -    | 0,4490 | 22,87    |
| Suppl. 14385/1                  | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 3 | 31/03/2017    | -                | -    | 0,4330 | 21,16    |
| Suppl. 14391/2                  | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 3 | 30/03/2017    | -                | -    | 0,4450 | 22,66    |
| Suppl. 14393/2                  | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 3 | 28/03/2017    | FS32             | FS31 | 0,4310 | 22,05    |
| Suppl. 14396/a                  | Sala 02 vetrina 16                                      | 03/04/2017    | -                | -    | 0,4591 | 22,86    |
| Suppl. 14415/2                  | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 2 | 29/03/2017    | -                | -    | 0,4404 | 22,36    |
| Suppl. 14426/2                  | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 4 | 30/03/2017    | -                | -    | 0,4580 | 22,84    |
| Suppl. 14435 (?)                | Ipogeo - magazzino visitabile - cassa 005               | 31/03/2017    | -                | -    | 0,4391 | 22,95    |
| Suppl. 14508                    | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 1 | 28/03/2017    | FS30             | FS29 | 0,4552 | 21,49    |
| Suppl. 14533/1 (?)              | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 4 | 28/03/2017    | -                | -    | 0,4340 | 22,31    |
| Suppl. 14650                    | Ipogeo - magazzino visitabile - scaffale 10             | 01/04/2017    | -                | -    | 0,4864 | 22,46    |
| Suppl. 15741/1                  | Ipogeo - magazzino visitabile - scaffale 07 - ripiano 4 | 31/03/2017    | -                | -    | 0,4729 | 22,59    |
| Suppl. 158 [...] = Suppl. 11173 | Magazzino vasi rosso, stanza 02, scaffale 06            | 05/04/2017    | -                | -    | 0,5093 | 24,90    |
| Suppl. 15809                    | Magazzino vasi giallo, Stanza 02, armadio 8, TOP        | 04/04/2017    | -                | -    | 0,4760 | 22,94    |
| Suppl. 16090/2 (?)              | Ipogeo - magazzino visitabile - scaffale 14 - ripiano 2 | 06/04/2017    | -                | -    | 0,5260 | 22,58    |
| Suppl. 16742                    | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 1 | 31/03/2017    | -                | -    | 0,4439 | 22,69    |
| Suppl. 16743 (?)                | Ipogeo - magazzino visitabile - scaffale 06 - ripiano 2 | 28/03/2017    | FS27             | FS28 | 0,4710 | 21,04    |
| Suppl. 16744 (?)                | Ipogeo - magazzino visitabile - scaffale 05 - ripiano 2 | 27/03/2017    | FS06             | FS05 | 0,4498 | 21,24    |
| Suppl. 16747/1                  | Ipogeo - magazzino visitabile - scaffale 05 - ripiano 2 | 30/03/2017    | -                | -    | 0,4751 | 22,49    |
| Suppl. 16760 (?)                | Ipogeo - magazzino visitabile - scaffale 08 - ripiano 4 | 04/04/2017    | -                | -    | 0,4300 | 21,22    |
| Suppl. 16770/2                  | Sala 02 vetrina 08 o ML sc 10                           | 05/04/2017    | -                | -    | 0,4989 | 22,96    |
| Suppl. 16771                    | Magazzino legni, scatola 011                            | 01/04/2017    | -                | -    | 0,4080 | 22,14    |
| Suppl. 16772/2                  | Magazzino legni, scatola 012                            | 01/04/2017    | -                | -    | 0,4832 | 22,28    |
| Suppl. 16773/2                  | Magazzino legni, scatola 013                            | 03/04/2017    | -                | -    | 0,4484 | 22,98    |
| Suppl. 16774                    | Magazzino legni, scatola 014                            | 04/04/2017    | -                | -    | 0,4730 | 22,25    |
| Suppl. 17045                    | Ipogeo - magazzino visitabile - scaffale 03 - ripiano 4 | 04/04/2017    | -                | -    | 0,4561 | 22,62    |
| Suppl. 19691/3                  | Sala 12 vetrina 06                                      | 27/03/2017    | -                | -    | 0,4000 | 21,94    |
| Suppl. 5288 Prov_575            | Ipogeo - magazzino visitabile - cassa 760               | 06/07/2017    | -                | -    | 0,4870 | 22,17    |
| Suppl. 8431                     | Sala 07 vetrina 04                                      | 03/04/2017    | -                | -    | 0,4458 | 24,68    |
| Suppl. 8471                     | Sala 07 vetrina 06                                      | 03/04/2017    | -                | -    | 0,4439 | 24,26    |

**Tab. 1B:** Results of the water activity (aw) value for the mummies, correlated with the acquisition temperature value Taw (°C) of the room where the research operations were carried out.



**Fig. 6:** Relationship between the number of mummies and the results of the water activity (aw) analysis.





**Fig. 7:** Fungi detected on textiles and soft tissues of mummies from the storage room (Ipogeo, magazzino visitabile) and from display cases. The pictures on the upper right show a contact plate sampling on a grass mat and the fungal growth on the agar plate after incubation. The fungi marked with an asterisk have been detected both on the contact plates and in the air sampling.

different fungi detected on the storage room material ( $n=17$ ) is substantially higher than the ones from the display cases ( $n=3$ ). In addition, in contrast to the storage room samples, approximately half of the contact plates taken from the exhibition room samples display no fungal growth at all. This result indicates that the exhibition room material has a lower fungal spore and mycelia load in comparison to the material from the storage room. Further comparison of the detected contact plate fungi with the results obtained from air sampling indicates the presence of air-borne fungi in all the material analysed (Fig. 7,

asterisks). For example, fungal species belonging to the genus *Penicillium* spp. were detected both on the material and in the air in the display cases. However, beside this acquisition and exchange of airborne fungal spores and mycelia, there still appear to be indigenous fungal communities present on different material. The fungal communities detected on the storage room textile or soft-tissue material on display clear sample-specific differences (Fig. 7). These differences become even more apparent when we take a closer look at the functional properties of the “material-specific” fungal species detected. Fungi

such as *Bjerkandera adusta*, *Aspergillus tubingensis*, *Cladosporium cladosporioides* and *Cytospora sacculus* were only detected on the textile/plant material.<sup>19</sup> For example, while sampling a grass mat using contact plates, we only observed the presence of one fungus, *Aspergillus welwitschiae*, which is known to be involved in the breakdown of fibrous plant material such as sisal<sup>20</sup> (Fig. 7). Taken together, almost all the fungi detected in the textile material are commonly found saprophytes involved in degrading plant remains. In contrast, the soft tissue harboured unique fungal species such as *Alternaria infectoria*, a saprophytic fungus known to thrive on skin tissue.<sup>21</sup> In addition, we detected several *Penicillium* species (e.g. *Penicillium chrysogenum*) on the soft tissues, known for their proteolytic potential.<sup>22</sup> There is therefore a clear indication of the presence of material-specific fungal communities.

## 5. Final considerations

In sum, our results indicate a still present biodegradational potential in the form of tissue-specific fungal communities (spores and mycelia), which could

become a biodegradative risk as soon as the environmental conditions change, for example, at water activity levels above 0.65 (aw), which promote fungal growth.<sup>23</sup> It is therefore of the utmost importance to keep the water activity levels of these unique cultural assets under constant control.

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## Notes

<sup>1</sup> Scattolin Morecroft, in *JEA* 92 (2006), pp. 278, 281.

<sup>2</sup> Moiso, *La storia del Museo Egizio* (2016).

<sup>3</sup> For an overview on the mummies from Donati's and Drovetti's collection, see Fiore Marochetti in Boano and Rabino Massa (eds.), *Mummie Egizie in Piemonte* (2012), pp. 5–6; Boano et al., *Mummie e mummificazione* (2015); Delorenzi, Grilletto, *Le mummie del Museo Egizio di Torino* (1989).

<sup>4</sup> Boano et al., *Le mummie del Museo Egizio di Torino* (2008); Marro, *Scavi Italiani in Egitto* (1930).

<sup>5</sup> Boano et al. in Boano and Rabino Massa (eds.), *Mummie Egizie in Piemonte* (2012), p. 21.

<sup>6</sup> Piñar et al., *FEMS Microbiology Ecology* 86/2 (2013); Piñar et al., *Extremophiles* 18/4 (2014).

<sup>7</sup> Michaelsen et al., *International Biodeterioration & Biodegradation* 58/3 (2006).

<sup>8</sup> White et al., in Innis et al. (eds.), *PCR Protocols: A Guide to Methods and Applications* (1990).

<sup>9</sup> Piñar et al., *FEMS Microbiology Ecology* 86/2 (2013).

<sup>10</sup> Altschul et al., *Nucleic Acids Research* 25/17 (1997).

<sup>11</sup> Cheftel et al. (eds.), *Biochimica e tecnologia degli alimenti* (1999).

<sup>12</sup> FprEN 16242.

<sup>13</sup> EN 15803.

<sup>14</sup> EN 15803.

<sup>15</sup> Labuza, in Cho-Kyun Rha (ed.), *Theory, Determination and Control*, 1975.

<sup>16</sup> Labuza, in Cho-Kyun Rha (ed.), *Theory, Determination*

*and Control*, 1975; Shin, *Oxygen-Free Museum Cases*, 1998; Samadelli et al., *Journal of Cultural Heritage* 14/6 (2013).

<sup>17</sup> Samadelli et al., *Journal of Cultural Heritage* 14/6 (2013).

<sup>18</sup> Labuza, in Cho-Kyun Rha (ed.), *Theory, Determination and Control*, 1975.

<sup>19</sup> Bensch et al., *Studies in Mycology* 67 (2010); Fan et al., *Fungal Biology* 119/5 (2015); Perrone et al., *Applied Environmental Microbiology* 72/1 (2006); Wang et al., *Canadian Journal of Microbiology* 49/11 (2003).

<sup>20</sup> Duarte et al., *Frontiers in Microbiology* 9 (2018).

<sup>21</sup> Dubois et al., *Mycopathologia* 160 (2005).

<sup>22</sup> Martín et al., *Meat Science* 62 (2002).

<sup>23</sup> Labuza, in Cho-Kyun Rha (ed.), *Theory, Determination and Control* (1975).

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