Species-specific detection of processed animal proteins in feed by Raman spectroscopy

Species-specific detection of Processed Animal Proteins in feed by Raman Spectroscopy

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Abstract

The existing European Regulation (EC n° 51/2013) prohibits the use of animals meals in feedstuffs in order to prevent Bovine Spongiform Encephalopathy infection and diffusion, however the legislation is rapidly moving towards a partial lifting of the "feed ban" and the competent control organisms are urged to develop suitable analytical methods able to avoid food safety incidents related to animal origin products. The limitations of the official methods (i.e. light microscopy and Polymerase Chain Reaction) suggest exploring new analytic ways to get reliable results in a short time. The combination of spectroscopic techniques with optical microscopy allows the development of an individual particle method able to meet both selectivity and sensitivity requirements (0.1 %w/w). A spectroscopic method based on Fourier Transform micro-Raman spectroscopy coupled with Discriminant Analysis is here presented. This approach could be very useful for in-situ applications, such as customs inspections, since it drastically reduces time and costs of analysis.

keywords: PAPs, Raman spectroscopy, species identification, chemometrics

1. Introduction

The outbreak of bovine spongiform encephalopathy (BSE) urged the European Union to take several decisions in order to avoid the transmission of its most probable causal agent through the food chain, which is a protein residue called prion. It is generally accepted that the most likely route of infection of cattle with BSE is by feeding cattle with infected processed animal proteins (PAPs). The commercially available PAPs appear as grinded dry meals and consist into two main fractions: i) the lightweight fraction, including muscle fibers, hairs and grease and ii) the heavy residual, containing the mineral fraction, bone fragments, tooth fragments, cartilage etc. The two fractions can be easily separated through a sedimentation procedure using high density solvent such as tetrachloroethylene. PAPs from different animal origin have peculiar features in terms of color and smell. mammalian PAPs are characterized by a high fraction of hard bones fragments, typical for high-size animals' skeleton structure. PAPs derived from swine slaughter processes has light ivory color, is very finely grinded and the unsaturated fat content is higher with respect to ruminant PAPs. Poultry and fish meal are characterized by darker color, pungent smell, rough grinding and the total fat content is mostly represented by saturated oils; the bones fragments in this case are mainly soft bones tissues with high cartilaginous content.

The legislation about the prevention, control and eradication of BSEs evolved a lot during the past 15 years through several EC regulations (Van Raamsdonk 2007). Particularly relevant are Regulation (EC) n° 999/2001 and Regulation (EC) n° 1069/2009 (Animal by-products Regulation) which prohibits the feeding of terrestrial animals of a given species other than fur animals with PAPs derived from the bodies or parts of bodies of animals of the same species (ban of intra-species recycling). After the publication of the TSE Road Map II (rev. 10) in 2010, a lifting of the ban about the use of PAPs from non-ruminants in non-ruminant feed could be considered, of course without lifting the existing prohibition on intra-species recycling. The most recent European Regulation (UE) n°56/2013 highlights that the availability of effective and validated tests to distinguish between PAP of different animal species should be a prerequisite of any possible reintroduction of non-ruminant PAP to feed other non-ruminant cattle, as well as a careful analysis of the risks of relaxation, regarding animal and public health. In other words the feed-ban lifting would turn into a revision of the present legislation, only if validated and accredited analytical techniques to determine the species origin of PAP will be available and if an efficient channeling of PAPs from different species will be in place.

In this concern, in 2012, the European Union Reference Laboratory for Animal Proteins in feedstuffs (EURLAP) validated a new Polymerase Chain Reaction (PCR) method which is able to detect very low level of ruminant material that may be present in feed and a validated method to detect porcine DNA is on the way. Official methods for the detection of ruminant DNA and optical microscopy lay down in Regulation (EU) 51/2013. Thanks to these official methods the feed-ban was partially lifted, and non-ruminant PAP are now allowed in fish feed. The microscopy method is based on the recognition of morphological characteristics of bone fragments, or other structures, e.g. muscle fibers, animal fur, teeth fragments, feathers etc. The fine image analysis using 10X, 20X and 40X objective magnifications allows PAP from terrestrial to aquatic animals to be distinguished in accordance with the osteocytes' *lacunae* morphology and bones peculiarities. Nevertheless, the confusing features revealed between mammalian and poultry PAPs do not allow a correct discrimination of the two classes using optical microscopy. On the other hand, PCR provides high sensitivity and specificity but it does not reveal the nature of the DNA trace sources. This represents a problem since ruminant DNA is present both in authorized (i.e. milk) and in not authorized (i.e. ruminant PAP) ingredients in feed. Another lack of the official methodologies is that they do not allow the quantification of animal origin constituents in feed. Both methods have a declared cut-off concentration around 0.1 % (w/w).

Other non-official methods, such as near-infrared spectroscopy (NIRS) (Murray, Aucott and Pike 2001;), near-infrared microscopy (NIRM) (Baeten et all 2005, Pavino et al 2009), liquid chromatography (LC) and olfactometry techniques were tested for the detection of PAPs in literature. LC methods are based on the detection of specific polypeptides. For example, carnosine is mainly present in mammals and anserine is mainly found in birds (Schőnherr 2002). On the other hand, LC methods are difficult to standardize, because polypeptides are usually strongly denatured because of the high temperature treatments required by Annex IV of Regulation (EC) 142/2011. Olfactometry is based on the detection of volatile non-specific agents (Campagnoli et all 2004) and it represents an interesting non-destructive and fast technique. Unfortunately, it turned out that the presence of fish material could mask the detection of proteins of land animals, even at a contamination level of 5 g/kg. Spectroscopic techniques are non-destructive methods that can be applied for *in situ* analysis in feed production plants or in farms, but the too high detection limit did not allow their diffuse application in official control laboratories yet. Anyway, the combination of spectroscopic techniques with optical microscopy could lead to an individual particle method, and reach the sensitivity required. Near and mid infrared spectroscopy, as well as Raman spectroscopy, are promising techniques because of their molecular specificity. The complex pattern of

vibrational peaks contains a lot of chemical information and it represents the sample's molecular fingerprint. A spectroscopic approach based on Fourier Transform Raman spectroscopy (FT Raman) for detection of PAPs in feeds is here presented. Moreover, a specific method based on the multivariate treatment of spectra for species recognition is shown and the principal advantages and disadvantages of this method are addressed in this work. In the big-data era modeling techniques are widely exploited to describe complex systems in many fields of research and for different applications (Valipour, Singh 2016). The aim of this study is to demonstrate that a multivariate classification models can provide a consistent tool for sample recognition, even if matrices are complex as feedstuffs and PAPs are. The major advantages of the proposed method, with respect to the established optical microscopy and PCR methods, are the reduction of time and costs of analysis, the automation and the objectivity of results, because of the low operator-dependence of Raman spectroscopy. After setting the classification model, a minimal time is required to operators to launch the Raman mapping analysis and no highly qualified operators are needed. The combination of spectroscopic techniques with optical microscopy and chemometrics permits to develop a highly sensitive and specific method. The molecular fingerprint collected using vibrational spectroscopy represents one interesting way towards the species specific-method, strongly required for the further European Regulations about intra-species recycling controls.

2. Material and Methods

2.1 Reagents and materials

Pure PAPs sample of category 3 (PAPs derived from animals suitable for human consumption) from four different species (bovine, swine, poultry and fish) and a generic feed were provided by the Veterinary Medical Research Institute for Piemonte, Liguria and the Valle D'Aosta (IZSTO). Tetrachloroethylene (specific gravity 1,62 g/cm^3) was purchased from Nova Chimica (Milan, Italy). Conical glass separation funnels with a content of 250 ml with Teflon or ground glass stopcock at the cone base were used for sedimentation procedure. Stopcock opening diameter ≥ 2 mm was used for sedimentation procedure. Laboratory press for tablets preparation with dial indicator to enable reproduction of force settings (E-Z™ Quick Table Top Press) was provided by International Crystal Laboratories, and it was used to prepare ≈0.3 mm thick tablets.

2.2 Sample preparation

106 The material was carefully mixed to obtain a homogenized sample. Pure PAPs samples were already milled,
107 whereas vegetal feed in pellets was grinded in a laboratory blender up to granulometry <0.5 mm. All reusable
108 equipment was carefully cleaned before use to avoid laboratory cross-contamination. Separation funnel pieces
109 and glassware were pre-washed manually and cleaned by using a brush with stiff synthetic hairs. A final
110 cleaning of sieves with acetone and nitrogen flux was recommended.
111 For the calibration set construction pure PAPs were used. The method sensitivity was evaluated through
112 standards meal samples with a known contaminant concentration. A commercial feed, previously tested with
113 classical microscopy method to exclude PAP contamination, was fortified with known amount of PAPs, ranging
114 from 0.1 to 10 % w/w. A reference sample spiked with PAP at 0.1 %w/w was prepared by the EURL-AP for
115 inter laboratory study and provided by the Italian Reference Laboratory (IZSTo).

116 In accordance with Regulation (EU) 51/2013 extraction and preparation of the sediment, a portion of 3 g of pure
117 PAP (accuracy of 0.01 g) of the ground sub-sample was transferred into the separation funnel or conical
118 bottomed settling beaker and 50 ml of tetrachloroethylene were added. The mixture was vigorously shaken for at
119 least 30 s and at least 50 ml more of tetrachloroethylene were added cautiously while washing down the inside
120 surface of the funnel to remove any adhering particles. For the contaminated feed analysis 10 g of feed was used
121 and two aliquots of 50 ml of tetrachloroethylene for separation. Both resulting mixtures were left to stand for at
122 least 5 minutes before the sediment were separated off by opening the stopcock and dried on a paper filter.
123 Sediment fraction was about 10 % of the whole sample of pure PAP.

124 *2.3 Scanning electron microscopy and EDX*

125 Scanning Electron Microscopy images of bone fragments were collected using Inspect F (FEI, Hillsboro,
126 Oregon), acceleration potential used was 10 kV. Samples were covered with 10 nm of Au/Pd alloy using
127 sputtering technology. Energy-dispersive X-ray spectroscopy was performed using Inspect F (FEI, Hillsboro,
128 Oregon), as well.
129 *2.4 Raman measurement*

130 Thin self-consistent tablets for Raman analysis were prepared using a laboratory press. This method is very rapid
131 and safe in comparison with microscope glasses preparation since solvents and drying time are avoided. This is a
132 very useful condition for Raman imaging, as in flat tablets all fragments lied exactly at the same distance from

the laser source, and each spectrum of a Raman map can be collected in suitable focus conditions. In this way focus was set only once before the Raman mapping analysis. Raman spectroscopy analysis was performed with a NXR FT-Raman Module Nicolet Series™ (Thermo Fischer Scientific, Waltham, USA) equipped with an InGaAs detector. The laser power of 0.8 W was used for the calibration set collection, whereas 0.3 W was used for the Raman mapping of contaminated feed samples. Raman spectra collection was optimized using 1064 nm excitation laser mounted on a Fourier Transform Raman instrument to minimize the fluorescence phenomena in competition with Raman signal. The wavenumbers range considered was 200 cm^{-1} – 4000 cm^{-1}. A resolution of 8 cm^{-1} was applied, and 256 scans were collected for each map point to obtain a S/N ratio higher than 10. For rapid screening tests fast Raman mapping was performed with 1 mm diameter laser spot (instead of 50 µm) and 64 scansions for each map point, instead of 256.

2.5 Calibration procedures

The row Raman spectra were treated for chemometric analysis by TQ Analyst™ 8.0 software. A preliminary correlation test was performed to attest a correlation between the spectroscopic features (variables) and the belonging class (responses). Then a consistent data set was collected so that the total variability of the system is described; then the discriminant analysis (DA) method was applied, to obtain a robust classification model. All calibrated models were validated through an external validation procedure by new test set.

3. Results and Discussion

3.1 Optical end electronic microscopy

The limits of the official optical method for identifying PAPs in feedstuffs suggest exploring new analytic ways to get more information from samples with simple and quick techniques. The heterogeneity of the matrices and the low limit of detection required by the legislation into force (0.1 %), represent the most challenge in setting an easy and fast method of analysis. In this study a "bottom up" approach was carried out in order to hit the target. First, pure analytes (i.e. the PAPs from different animal species) were analyzed, to prove that Raman technique was able to characterize the PAPs with high specificity. Interferences of feed materials of vegetal origin were ignored at first.

The fraction of sedimented PAPs in TCE can represent variable percentage of the whole sample weight depending on the species (for instance, processed bovine proteins have a higher sedimentable fraction compared to processed swine proteins). The most part of sediment contains bone fragments as demonstrated by and EDX

161 analysis (Energy-dispersive X-ray spectroscopy), which revealed the typical composition of mineral biological
162 tissue containing Ca, P, Na, O, H.
163 The optical identification of animal fragments in the sediment fraction is based on the systematic observation of
164 fragments lied on a microscope glass using 10X, 20X and 40X objectives. Optical images collected in
165 transmission mode of fish and terrestrial animal bone's fragments are shown in Fig. 1. In the optical images
166 osteocytes *lacunae* can be easily identified as well as the *lacunae* ramification. The shape and size of the
167 osteocytes' *lacunae* and their ramifications are the most specific features for the discrimination of PAPs of
168 aquatic and terrestrial animals. Bone fragments are stained with red alizarin dye to facilitate the identification, as
169 suggested in the official procedure. However, this recognition can be lead only by well-trained operators and, in
170 any case with some level of uncertainty.
171 Fig.1
172 More accurate information about bone fragments morphology is collected by Scanning Electron Microscopy to
173 investigate fine structural differences among different animal species. Unfortunately, after the grinding process
174 bone fragments show a damaged structure; SEM images of bone fragments permit to identify the structural
175 components of bones described in literature. In particular the most common building blocks of bones such as
176 collagen fibrils, mineral plates, un-mineralized matrix, non-fibrillar organic material (mostly made of
177 proteoglycans and glycoproteins) can be identified using SEM. (Thurner et all 2006 a; Thurner et all 2006 b). For
178 example, SEM images of bone fragments from different species shown in Fig. 2a represent fibrils coated with a
179 large amount of non-fibrillar organic material. In Figure 2b osteocytes *lacunae* can be identified with a good
180 perception of their 3D structure.
181 Fig.2
182 Unfortunately SEM images do not reveal to be more informative than optical microscopy in this domain. It is not
183 possible to identify very characteristic structures that could be univocally associated to one animal species. All
184 PAPs samples analyzed with SEM presented fragments with similar morphologies and it was not possible to
185 identify some very specific indicator that allows a certain classification of bones from different animal species.
186 Even if it is not excluded that an accurate study using powerful images analysis techniques could provide some
187 interesting results in the future. However, neither recognition software, nor complete libraries are now available
188 about bones fragments using SEM. What is more, it seems to be worthless to use such an expensive technique
189 for morphological analysis, the procedure is time consuming and unsuitable for automation. Therefore, even if

well trained operators could perform the microscopic official methods rather easily, it is not possible to indicate SEM as a robust method for animal species recognition in feed.

3.2 Raman characterization of meat and bone meals

Automatic spectrometer coupled with microscopy technology could represent a valuable tool for implementing the existing methodology. In this way morphological information provided by the microscope and chemical information provided by Raman spectroscopy could be merged in order to obtain the best recognition of animal fragments and their species of origin. Raman characterization of the two separated fractions (i.e. sediment and flotate) revealed that the chemical nature and optical and physical features of the flotate fraction make it difficult to collect Raman spectra. Fluorescence phenomena and the huge heterogeneity of samples would represent a great limitation for a possible routine Raman analysis for PAPs. Otherwise, the sediment resulted to be more suitable for Raman characterization. Sediment fraction of PAPs was particularly resistant to laser power, therefore 0.8 W laser power was set for pure PAPs analysis; this permits to reach S/N ratio out of 15 with 256 scansions. Random variability of spectra of different fragments of the same PAP sample involved only the background intensity of the entire spectra; no differences, neither in mutual intensity of peaks nor in peaks' shape were recorded. A normalization procedure of spectra revealed that spectra of the same species perfectly overlapped. Signals can be assigned to bone and meat chemical components. In fig. 3 a model spectrum of PAP is shown with the attribution of the Raman bands to the corresponding chemical functional groups (Socrates 2001). The attention was focused on the band at 960 cm^{-1} due to hydroxyapatite compound (Figueiredo, Gamelas and. Martins 2014) which is characteristic for bone's fragments. This signal is suitable as reference signal and it could be successfully used as an "alert signal" during screening analyses. The presence of such peak could therefore represent the very first warning about a PAP contamination in the sample.

Fig 3.

The spectra profile was very similar for all tested species. Differences among species are basically in shape, mutual intensity and baseline trend of spectra as it can be noticed in the Fig 3b.

3.3 Multivariate data treatment and classification

Since spectra of different PAPs look very similar, a monovariate analysis of a single Raman peak can not lead to any significant result. Contributions of both the organic and the inorganic components result in a characteristic

pattern of spectroscopic signals, which can be interpreted only through a multivariate approach. Calibration procedure requested the preliminary collection of a training set made of about 80 samples spectra; than discriminant analysis method was applied to obtain a classification model.

No consistent separation was achieved when all species (bovine, swine, fish, and poultry) were considered contemporarily. Unfortunately, any optimization such as mathematical pretreatment and variable selection was straightforward for a classification model composed of four classes. The test set validation failed for 25% of validation spectra in the best case, therefore the simultaneous classification of all species was excluded and a two steps procedure was developed. Taking into account preliminary observation made on the data set, a two class model was developed: initial separation of mammals (i.e. bovine and swine) from non-mammals (i.e. fish and poultry) animals was set, in accordance with visible spectra similarity. Appreciable improvements in classification model were obtained by setting a model composed of two classes: i) mammals (bovine and swine) and ii) non mammals (fish and poultry) (Fig. 4a). The obtained DA model was calculated considering 10 principal components, which correspond to a cumulative explained variance of 95 %. All spectra were treated by standard normal variate (SNV) for minimizing pathlength differences. The method underwent two different validation tests: leave-one-out cross validation as an internal validation procedure provided fully correct answers. Then external validation test was performed using an external test set. Also in this case no incorrect classification was obtained.

A second classification step was then added to recognize the single species. Other two dual class models were optimized to discriminate bovine from swine meal (Fig 4b) and fish from poultry meal (Fig 4c) using a similar strategy. Fish/poultry separation model gave satisfying results; 8 PCs were used, corresponding to a cumulative explained variance of 97 % and 0% of misclassified during external validation were obtained. Otherwise, bovine/swine model resulted to be harder to be optimized, as the variability between swine and bovine spectra was slighter. Anyway 0% misclassified of validation samples were obtained using 6 PCs which show a cumulative explained variance of 94%. Thus, a two steps procedure for an exhaustive specific recognition of animal origin of PAPs was implemented and validated for pure PAPs samples.

Fig. 4

3.4 Set up of the innovative analytical methodology

In order to test the applicability of the proposed analytical method for the identification of PAPs in feeding stuff an analytical procedure was developed and assessed. The micro Raman method proposed was built on the basis of official optical microscopy method, and paves the way to a possible automation of the procedure, implementing an automatic preliminary scan using Raman imaging. A procedure scheme of the whole innovative analytical method is shown in Figure 5. The automatic Raman imaging enables the operator to manage his working time in a more efficient way, leaving to the instrument the commitment of scanning the samples looking for the animal fragments. Moreover, a species- specific analysis could be carried out.

Figure 5.

Since high quality spectra collection would require a few minutes and the area to be analyzed is about 0.5 cm^2, the time of analysis would be too long for routine applications. Therefore, the analytical method was split into two phases: i) screening step, by fast Raman mapping of the whole tablet's area with 500 µm step-size, 1 mm laser spot and 64 scansions for each map point, as mentioned in M&M section, for preliminary suspect fragments identification; ii) a more accurate spectrum collection, suitable for species recognition. After collection, the screening map was profiled according to the Raman intensity at 960 cm^{-1}, which represents a specific peak for bones. This peak is usually intense, sharp and visible even in fast spectra collection. A color scale related to 960 cm^{-1}intensity was associated to the x-y position on the map, to recognize suspect fragments (Fig. 6). After the entire map collection the operator was requested to lead the laser spot on those alert points, using the powered sample stage, and collects new high quality spectra for species identification.

Fig. 6

The method sensitivity was tested using a reference sample contaminated with PAP at 0.1% w/w which is the currently accepted limit of detection (LOD). The reference sample was prepared by the EURL-AP for an inter laboratory study and provided by IZSTo. The proposed Raman imaging method allowed the identification of PAPs up to 0.1 % the method was set as a reiterative method. The sample can be declared "PAP-free" after six Raman map collections. The low resistance of sediments to high laser power used for species-specific calibration models and the interferences due to feed matrices during the high specific spectra collection may affect the results. Nevertheless, these two issues did not lead to any mislead when the screening map was acquired with 0.3 W laser power and for PAP's fragments of dimensions upper then 100 µm.

4. Conclusions

In this work a method to identify the presence of PAPs in feed was developed and validated, as well as a species-specific analysis for the classification of PAPs found in contaminated feed. The suitability of Raman spectroscopy for the automatic identification of PAPs contamination in feed up to the existing LOD was demonstrated. The most sources of error of this work were related to the meal granulometry and matrix heterogeneity which made it difficult to reach very low sensitivity. These drawbacks could be solved adding at the top of the analytical procedure a grinding, homogenization and sifting step to obtain a more suitable powder for accurate contamination analysis. The validated Raman method is supposed to represent a semi-automatic screening method for intra-species recycling control, to support optical microscopy official method. All the analyses carried out in this study allows us to conclude that the combination of the sensitivity to molecular structure of Raman spectroscopy with optical microscopy can result in an effective method for the detection of PAP fragments in feedstuffs in a green-chemistry view. This method provides not operator dependent and time effective response. Indeed, after setting the classification model, a minimal time is required to operators to launch the sediment Raman mapping analysis and no high-qualified operators are needed. With this respect, future perspectives of this work are the revalidation of the proposed methodology directly in the control organisms' laboratories and inter-laboratory comparison studies to attest the wide scale reproducibility of the Raman methodology for the detection of animal origin contamination in feed. Moreover, in the future a similar analytical approach will be tested to promote a green analytical method also for new feed components such as insect meals. This automatic approach could be very useful for on-site applications, such as product official controls at the EU borders, as well as for custom inspections. In particular, avoiding sample delivery to a trained laboratory, time and costs of analysis would be drastically reduced.

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FIGURE LEGENDS

Figure 1– a,b) terrestrial bone; c) fish bone; d) fish cartilage images. All images are purchased by IZSTO.

Figure 2– a) Bovine (fibrils coated by non-fibrillar organic material); b) fish (osteocyte holes); c) poultry (pressure fracture in bone tissue); d) swine bones fragment.

Figure 3– a) typical Raman spectrum of PAP sediment with the characteristic signals assignments. The hydroxyapatite peak, relevant for further analysis is highlighted in a rectangular box. b) FT-Raman spectra of PAPs from swine, bovine, fish and poultry compared, the scale is normalized.

Figure 4– scores plot of optimized separation models for a) bovine-swine vs. fish-poultry; b) swine vs. bovine; c) fish vs. poultry.

Figure 5– Analytical method scheme of identification and recognition of PAPs in feedstuffs.

Figure 6– Raman mapping of feed tablet contaminated at 0.1 % with bovine PAP.

Figure 1

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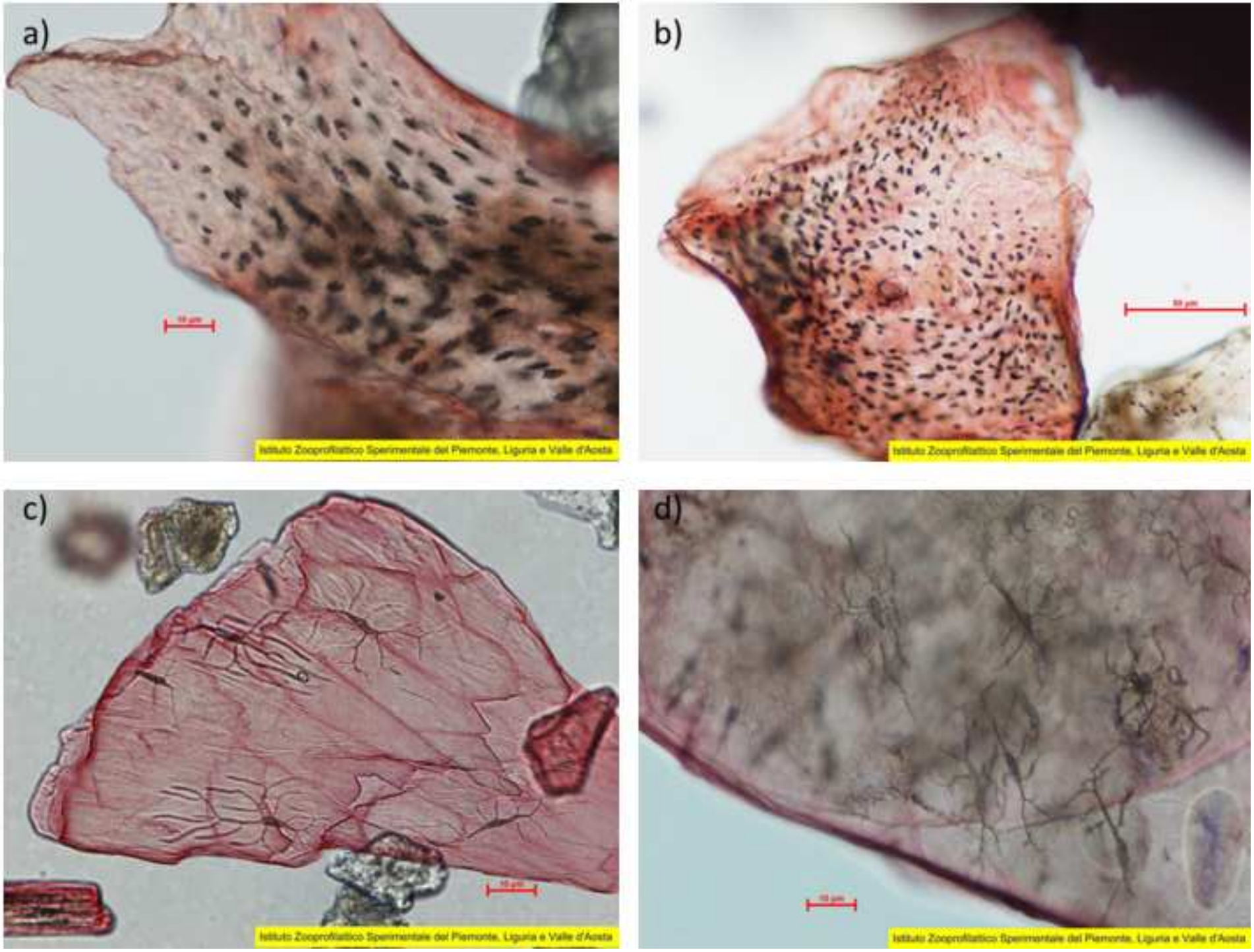

Figure 2

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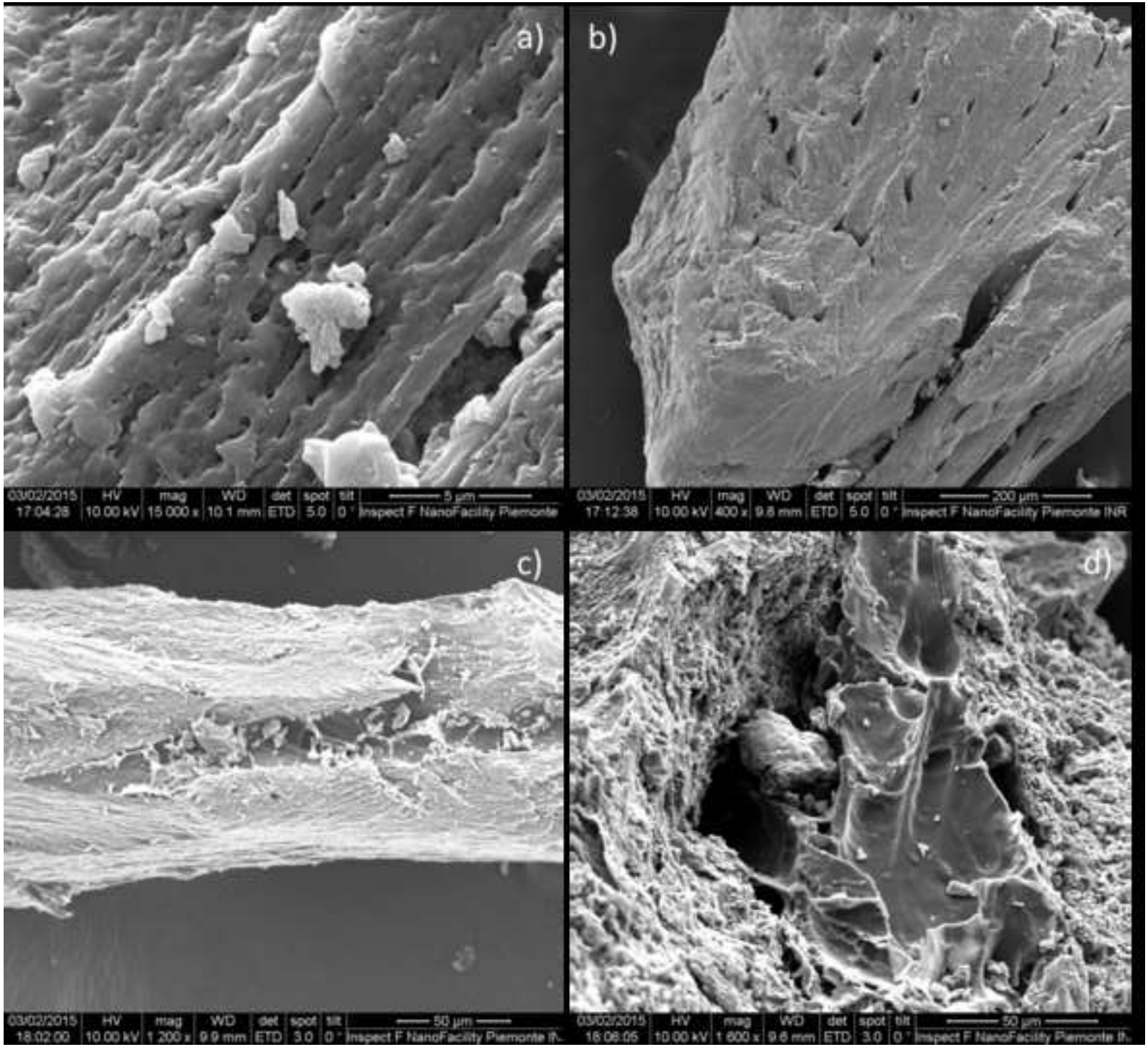

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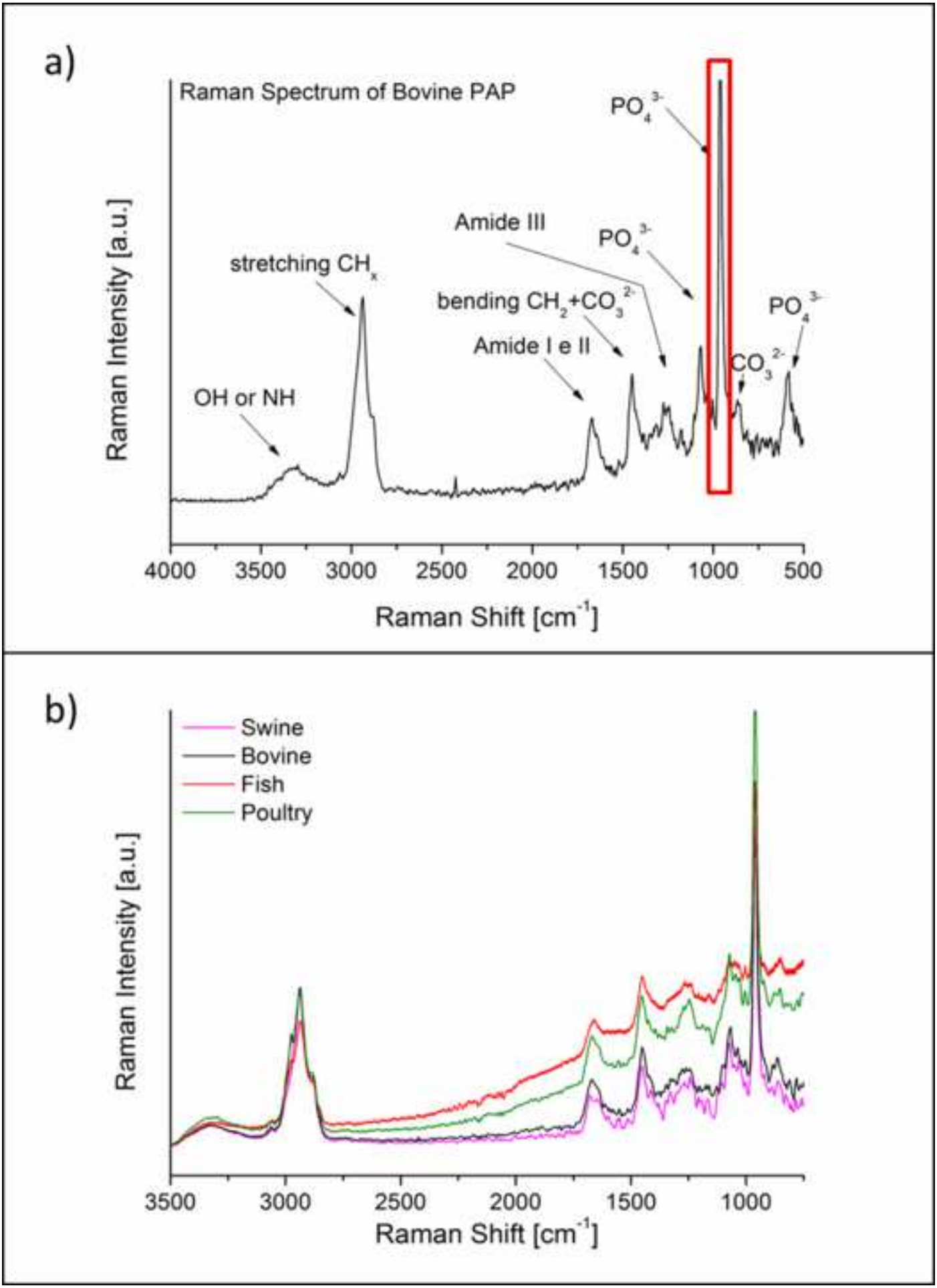

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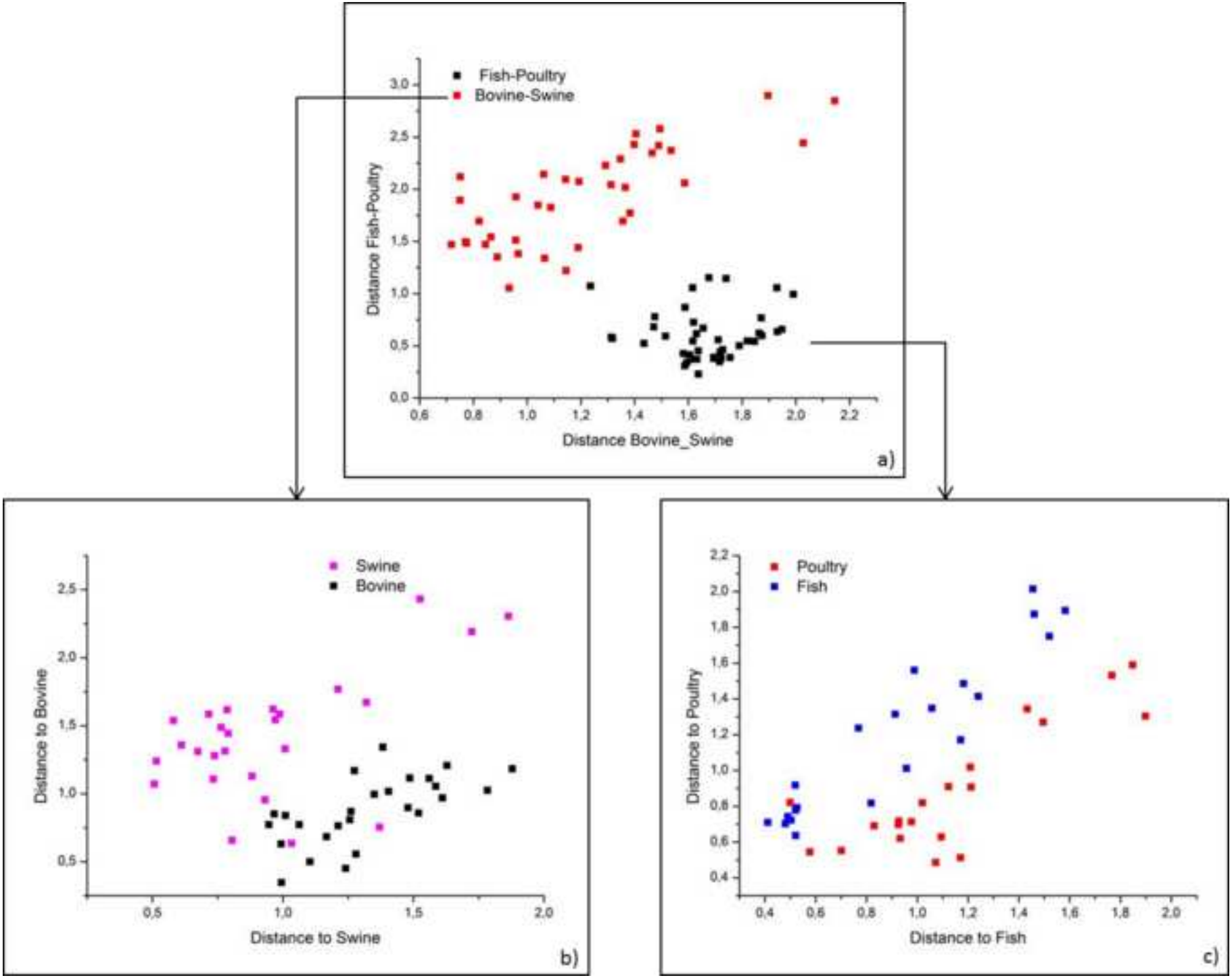

Figure 5

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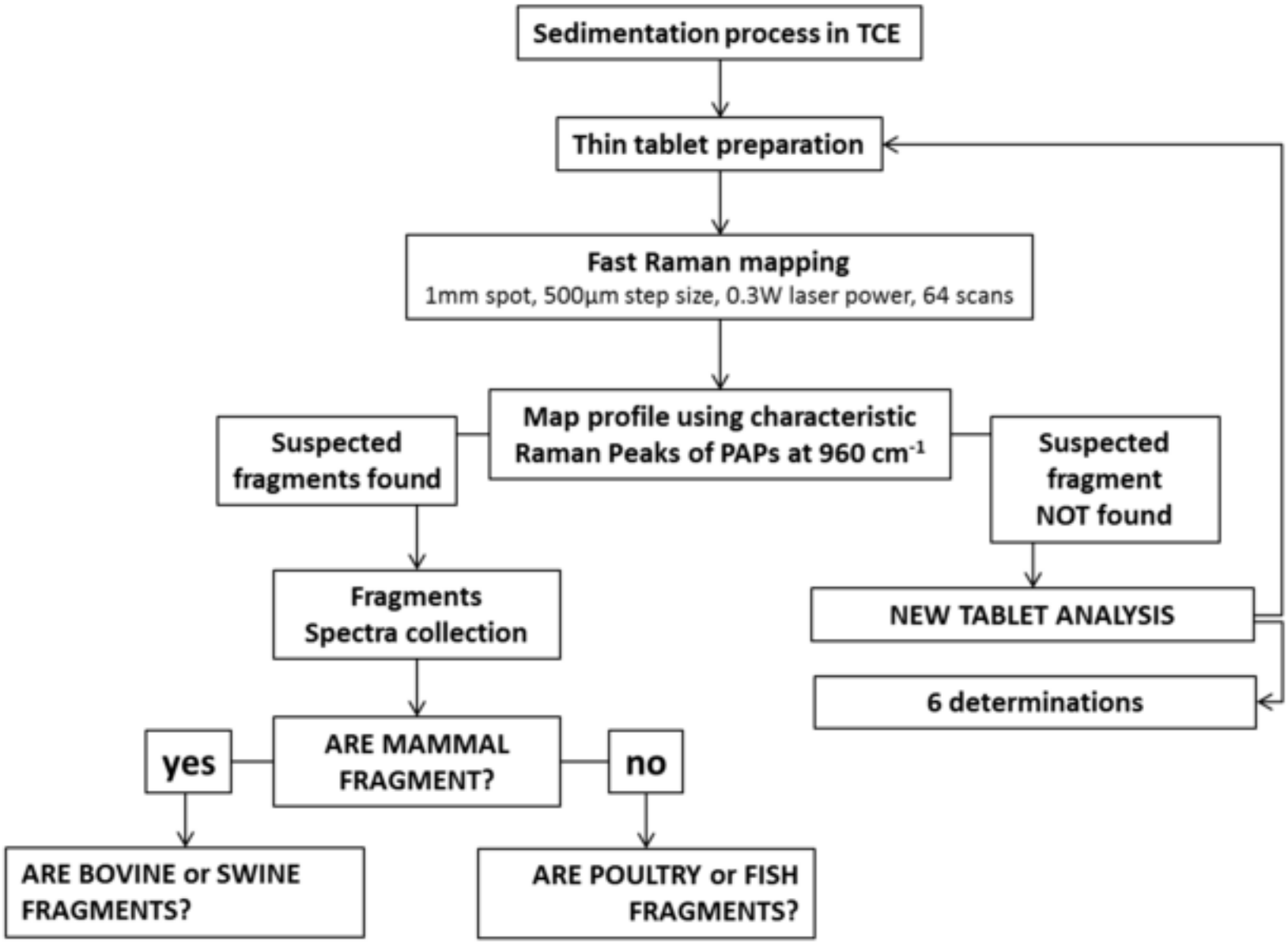

Figure 6

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