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Texture classification of particle size distribution data measured with laser diffraction method using different water types**

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Abstract. Laser diffraction measurement (LDM) is an accurate, fast, and reproducible method for measuring the particle size distribution (PSD), which is the basis for texture determination. However, LDM might yield different results from those provided by previously used sedimentation-based methods and even by other LDM measurements, depending on inter alia the applied instruments, their geometry, sample preparation, and/or pretreatment methods. It is also not yet generally known how these deviations affect the texture classification of soils. In our work, results of nine different texture classifications of eight soil samples were compared using confusion matrices based on PSD data obtained by: a) the sieve pipette method (SPM) after removal of binding agents between elementary particles; b) LDM measurement (without preparation) in distilled water and tap water, with pretreatments as follows: 1) without a dispersing effect, 2) using Calgon, 3) using ultrasound, or 4) applying their combination. Our results showed that the texture classification might shift by more than two classes due to either the type of measurement or the chemical or mechanical disaggregation method used, the quality of aqueous media, the variation of soil properties, or the interactions occurring in soil-liquid phase-dispersant systems. The standardisation of the LDM requires the elimination of these sources of error.

Keywords: pretreatment, Calgon, ultrasound, soil texture classification, aqueous medium

1. INTRODUCTION

Soil texture expresses as a qualitative variable of the size distribution of elementary particles (PSD). It depends primarily on the mineral composition of the soil, thus it is less variable over time than soil structure. Texture directly affects many other soil properties (*e.g.* specific surface area, porosity, bulk density) and determines complex soil characteristics such as the soil quality (Dexter, 2004), agronomical categories (Jadczyszyn *et al.,* 2016), bacterial biomass, diversity (Seaton *et al.,* 2020), nutrient availability, organic matter dynamics (Scott *et al.,* 1996; Plante *et al.,* 2006; Zacháry *et al.,* 2024), functional potential (Bouma *et al.,* 2016), sustainability to erosion and erodibility (Gupta *et al.,* 2024), and hydrological properties (Várallyay, 1985; Behera and Shukla, 2015; Bouma, 2016; Dewangan *et al.,* 2023), as well as the migration and transport of pollution (Weaver *et al.,* 1994). Hence, it is used as a diagnostic criterion in soil classification (Bieganowski *et al.,* 2018).

Particle size fractions (PSF) (*e.g.* the percentage of clay, silt, sand) are commonly determined from PSD data. Texture is classified based on PSF. Knowledge of PSD provides essential information in various fields of agricultural,

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earth, and environmental sciences (Gee and Bauder, 1986; Miller *et al.,* 1988; Varga *et al.,* 2019; Dewangan *et al.,* 2023; Gresina *et al.,* 2025).

Elementary particles can be grouped into three or more particle size fractions, which may vary between countries. Although the triadic grouping is the most common (clay, silt, sand); it is not uniform, as the size limits of the elementary PSF may differ (Nemes *et al.,* 1999; Makó *et al.,* 2017) and have changed over time (Martín *et al.,* 2018).

According to the Hungarian standard (MSZ-08-0205-78), the thresholds of these three PSF groups are 0.002, 0.05, and 2 mm for clay/silt/sand fraction corrected the limits of Atterberg (1912) (0.002, 0.02, and 2 mm), while the international standard (ISO 11277:2009(E)) defines the upper size limit of the silt fraction as 0.063 mm, according to the American Geophysical Union proposal, modifying the 0.05 mm size limit used up to now.

PSF determination, thus the texture classification too, might lead to different results, because samples used in the field or for laboratory analysis (<2 mm) might be different. The number of texture categories may also vary and, in some cases, special categories other than the defined ones may be applied (*e.g.* for mapping the "peat" and "coarse skeletal parts" categories – Szabolcs, 1966; Jassó *et al.*, 1989).

The United States Department of Agriculture (USDA) texture charts developed in the early 1900s in an effort to achieve standardization classify soils into 12 texture classes, primarily based on their clay, silt, and sand content. However, in different countries, disciplines may use various texture diagrams (*e.g.* horizontal, vertical, and diagonal), on average 12-18 groups (Bormann, 2010; Richer-de-Forges *et al.,* 2024). The applied size limits are always drawn "by necessity" (as between PSFs, it is primarily empirical by self-similarity, mineral composition, fractal geometry, *etc.*) (Richer-de-Forges *et al.,* 2024).

These texture classes are the primary input parameters and grouping variables for other parameters in hydrological software programs (ROSETTA – Schaap *et al.,* 2001; TALAJTANonc – Fodor and Rajkai, 2005), hydrological models (HYDRUS – Šimůnek and van Genuchten, 2008; SWAT – Arnold *et al*., 2012), and environmental modelling (HSSM – Weaver *et al.,* 1994; PLSI simulator – Guarnaccia *et al.,* 1997; STOMP – White and Oostrom, 2006; Srivastava and Valsala, 2023). The PSFs of soils as continuous variables (percentage of fractions) or texture derived from them are important elements of so-called pedotransfer functions developed for the characterisation of *e.g.* hydrological properties of solid media in modelling applications (Wösten *et al.,* 2001; Pachepsky and Rawls, 2004; Rajkai *et al.*, 2004; Vereecken *et al.*, 2010; Rajput *et al.,* 2024). PSFs can also be used as a grouping variable (in classPTFs – Wösten *et al.,* 1995; Tóth *et al.,* 2015; Richer-de-Forges *et al.,* 2024). It may therefore be necessary to harmonise PSF limits and texture groups, since texture, as an aggregate characteristic of PSD, allows simplification and facilitates the design of management practices and environmental interventions (Nemes *et al.,* 1999). This effort is important despite the fact that, depending on the use of texture data (in hydrological modelling, agronomical purposes, *etc.*), different PSF limits would be appropriate (Martín *et al.,* 2018).

The current needs for texture data in agricultural and environmental practice and technological advances have given a great boost to the use of remote sensing and/or satellite data in the last 30 years (Mgohele *et al.,* 2024) and the development of field and laboratory PSD measurement methods and procedures based on spectroscopic principles (Mancini *et al.,* 2024) or by image analysis (Srivastava *et al.,* 2021). Due to the widespread use of texture data and despite significant technological innovations in measurement techniques, the question may arise of what standardisable PSD measurement procedure could serve as the basis for a uniform texture classification. Large amounts of remotely sensed data used to determine texture can only be indirectly related to PSD values. Thus, although the "law of large numbers" naturally allows for an estimate that can be considered statistically accurate, there is a significant source of error in the robustness of the estimation. However, the references for these approaches are still the so-called "lab and cost-intensive" methods (necessity of "direct methods" for "indirect methods" – Wösten *et al.,* 1995), such as the commonly used sedimentation-based procedures (pipette, hydrometer method), which gives an opportunity for accurate determination of the PSD of all investigated soil layers with reliable results in field-collected samples. These methods are commonly used to determine texture data previously for mappings.

Nowadays, nearly 400 methods are known worldwide for the determination of texture (from hand-feel soil texture determination to remote sensing data collection). There are nearly as many protocols for determining PSD indirectly and texture in practice, such as the most widely used sedimentation-based methods, particle counting, microscopic (TEM, SEM) and image analysis methods, *etc.* (Syvitski, 1991; Richer-de-Forges *et al.,* 2024; Orhan *et al.,* 2022). Among the methods employed currently, research has highlighted the laser diffraction method (LDM) as fast, accurate, and reproducible measurements of PSD and aggregate size distribution (ASD) (Kovács, 2008; Sochan *et al.,* 2012; Yang *et al.,* 2015; Fisher *et al.,* 2017; Scott *et al.,* 2024). However, there is still ongoing standardisation of these measurements (Ryżak and Bieganowski, 2011; Scott *et al.,* 2024). These multichannel measurements (detailed determination of particle size distribution) could offer the possibility of comparing texture boundaries and conversion between PSF results per country and be fast and reproducible enough for practical use even if there are also some drawbacks reported in the literature. An important issue that still needs to be resolved today is that the size limits of particles may be different for various measurement principles (settling particle diameter, optical diameter measured, or the optical and geometrical behaviour of the components (refractive or adsorption index) affecting the measurement results differently (Tyugai *et al.,* 2010). The differences between the PSD values determined by LDM and conventional methods indicate that the determination of clay and sand (coarse sand) fractions may be subject to generally significant error (Buurman *et al.,* 2001; Polakowski *et al.,* 2015; Mattheus *et al.,* 2020; Stevenson *et al.,* 2023; Tomášová *et al.,* 2025). This can be partly avoided by developing different conversion options, for the clay/silt threshold (Konert and Vandenberghe, 1997 – 8 μm; Makó *et al.,* 2017 – 7 μm). However, a major difficulty in the comparability of the different measurement results is that the results are also influenced by the preparation (removal of binding agents, organic matter, possibly carbonates and sesquioxides) and pretreatment procedures (applying ultrasound and/or dispersing agents, stirring, circulation, pre-soaking (Chappell, 1998; Virto *et al.,* 2011; Madarász *et al.,* 2012; Polakowski *et al.,* 2023; Labancz *et al.*, 2024), and the measurement setup (devices and accessories) (Shein *et al.,* 2006; Makó *et al.,* 2017; Bieganowski *et al.,* 2018; Varga *et al.,* 2019). The need/lack of preparation can be assessed differently depending on the soil properties (in standards it is optional); it is not possible to identify only one theoretically appropriate procedure in all cases and for all goals (Orhan *et al.,* 2022), and it is necessary to consider how informative the results are from a practical point of view or in terms of use (Martín *et al.,* 2018).

In terms of cost, LDM requires a large initial investment, making it less accessible to small laboratories. The sieve-pipette method (SPM) has a lower initial cost, requiring only sieves, pipettes, and standard laboratory equipment. However, the LDM operating costs are relatively lower over time, as it reduces the need for chemical reagents and consumables. One of the main advantages of LDM is its speed and automation, which makes it advantageous in time-sensitive applications. LDM can analyse a sample, including dispersion and measurement, in 5-10 min. In contrast, sieve-pipette analysis takes hours per sample, involves multiple steps (sieving, settling, pipetting), and requires constant human presence. The greater reproducibility in LDM due to automation reduces human errors, while sieve-pipette methods can introduce human-dependent variability. Another big advantage of LDM measurements is that they require much lower soil sample amounts than SPM measurements (0.5-1 g compared to 10-30 g).

LDM user manuals and SPM standards (*e.g.* Beckman-Coulter, Malvern, Horiba, Fritsch; ISO 11277:2009(E)) provide no precise but only general information on the quality parameters of the liquid phase to be used for the measurement. However, literature reports suggest that the chemical parameters of liquid media have a considerable influence on the results of microaggregate stability tests with LDM (Fristensky and Grismer, 2008) and on the determination of PSD (Shein *et al.,* 2006; Mason *et al.,* 2011; Tan *et al.,* 2017; Bieganowski *et al.,* 2018; Labancz *et al.*, 2024). Moreover, there is a limited literature on how these differences can affect the texture classification of soil samples.

In our study, we aimed to answer the question of how different pretreatments and their combinations in particle size distribution determination affect the texture classification of soils. The following issues were examined in our investigation: a) To what extent does the chemically different liquid media used determine the texture classification based on the results of PSD measurements with a laser particle analyser; b) How different are the results of texture classification when the PSD determination is performed with the sieve-pipette method (SPM) after the removal of interaggregate binding agents (organic matter, $CaCO_3$, and sesquioxides) and with the laser diffraction method (LDM) after various pretreatments (even without pretreatments), c) if there is a difference, which soil properties are responsible for it and d) how does the use of chemical and/or physical dispersion (Calgon and/or ultrasound) or no pretreatment influence the measurement results and the texture classification in the case of soils with various physical and chemical properties.

2. MATERIALS AND METHODS

Eight disturbed soil samples (A and/or B horizons from six sampling sites) representing some of the main soil types in Hungary (classified according to WRB (IUSS Working Group, 2006), with different physical, chemical, and mineralogical properties (Tables 1, 2), were used for our research. First, we aimed to include common layered soil types (Cambisol, Luvisol) that, due to their layering, allowed the comparison of different horizons (A and B). This enabled the analysis of differences between surface humus-rich layers and deeper accumulation horizons, providing insight into their contrasting properties. Second, we prioritized soils with extreme properties, as their unique chemical or physical characteristics may lead to different behaviour in measurement conditions (*e.g.*, high sodium content, significant clay content, higher humus and carbonate levels, or hydromorphic characteristics).

Basic physical and chemical properties of air-dried (<2 mm) samples were determined according to the appropriate Hungarian standards (MSZ 0205:1978 and MSZ 0206:1978). The organic matter content was measured with the Tyurin method (Tyurin, 1931). An Eijkelkamp wet sieving device was used for the determination of macroaggregate stability (WSA – Kemper and Rosenau, 1986). X-ray diffraction (XRD, PHILIPS PW1710) mineral composition of <2 μm fraction of soils and particle size distribution measured with the sieve-pipette method with complete pretreatment (removal of inter-particle binding agents: $CaCO_3$ with HCl, organic matter with H_2O_2, and

Table 1. Chemical and physical properties of the investigated soils

Code	WRB soil classification, Location	Genetic horizons (cm)	Clay + Fe-ox	Silt	Sand	SOM	$CaCO_3$ (%)	CEC	Na^+	$pH_{(DW)}$
			(%)							
			SPM PSD*					(mg Eq 100 g^{-1})		
KAR	Vertic Stagnic Solonetz (Clayic)	B 5-30	51.09	45.90	0.88	2.00	0.13	40.85	20.63	6.92
KEA	Hortic Terric Cambisol (Dystric, Siltic)	A 0-30	21.09	33.13	44.28	1.45	0.05	11.84	0.14	7.04
KEB	Hortic Terric Cambisol (Dystric, Siltic)	B 30-50	22.90	33.87	42.29	0.93	0.00	12.38	0.13	6.83
VAA	Cutanic Luvisol (Siltic)	A 0-20	15.27	29.35	54.05	1.33	0.00	10.36	0.12	6.59
VAB	Cutanic Luvisol (Siltic)	B 20-50	22.30	26.56	50.49	0.65	0.00	12.78	0.15	6.64
MSZ	Vertic Gleyic Luvisol (Manganiferric, Siltic)	B 20-50	38.96	25.93	34.61	0.49	0.00	16.78	0.17	5.74
KÁP	Vermic Calcic Chernozem (Anthric, Siltic)	A 0-30	27.60	51.68	7.50	3.70	9.52	30.25	0.25	7.83
KIS	Gleyic Vertisol (Clayic)	A 0-30	53.88	41.19	1.05	3.89	1.10	35.69	0.29	7.51

Clay: <0.002 mm; Silt: 0.002-0.05 mm and Sand: >0.05 mm; *SPM PSD: Particle size distribution (sieve-pipette method – ISO 11277:2009(E)) where solid part of the soil is 100%; Clay+Fe-ox means the eliminated Fe-oxi/hydroxides and clays as binding agents from soil samples and CEC is the cation exchange capacity of soils. (Different limit from the standard (0.05 for sand/silt) was used because this allows texture classification with texture triangle). Code of soils represents the name of the closest city to the sample site and the symbol of the layers, if necessary: KAR – Karcag; KEA and KEB – Keszthely; VAA and VAB; Várvölgy; MSZ Magyarszombatfa; KÁP – Kápolnásnyék and KIS – Kisújszállás.

Table 2. Mineral composition of <2 μm fraction of soil samples determined by X-ray diffraction (XRD, PHILIPS PW1710) and water stable aggregates of the investigated soil samples

Code	Mineral composition (%)									WSA (%)
	Sw-Cl	I	Cl/Ka	Q	K-F	Pl	Ca	Do	Go	
KAR	4	15	5	62	2	12	0	0	0	20.84
KEA	2	10	4	70	2	12	0	0	0	53.40
KEB	2	10	5	68	2	12	0	0	2	38.47
VAA	2	3	2	76	7	10	0	0	0	87.57
VAB	5	5	3	70	4	10	0	0	3	38.38
MSZ	5	8	6	62	3	6	0	0	10	44.41
KÁP	2	7	6	58	5	10	10	2	0	64.56
KIS	4	20	4	60	2	10	0	0	0	59.14

Sw-Cl is the amount of swelling clay; I mean illite; Cl/Ka are chlorite and kaolinite; Q is quartz; K-F is K-feldspar, Pl is plagioclase; Ca is calcite; Do is dolomite, Go is goethite and WSA is the percentage of water stable aggregates according to Kemper and Rosenau (1986). Code of soils represents the name of the closest city to the sample site and the symbol of the layers, if necessary: KAR – Karcag; KEA and KEB – Keszthely; VAA and VAB; Várvölgy; MSZ Magyarszombatfa; KÁP – Kápolnásnyék and KIS – Kisújszállás.

Fe-oxides/oxihydrates with citrate-dithionite-bicarbonate – ISO 11277:2009(E)) were determined in our previous research (Barna *et al.*, 2015).

The particle size distribution (PSD) of soil samples in three repetitions (3-5 replicates per sampling) was measured with the laser diffraction method (LDM) using Malvern, Mastersizer 3000 equipment with the Hydro LV dispersion unit ($V = 600\ cm^3$) (according to the methods of Makó *et al.* (2017) and Polakowski *et al.* (2021). General settings were used, *i.e.* the pumping and stirring speed during the measurements was 2750 rpm (Makó *et al.,* 2022). Prior to the measurement, the system was degassed and 0.5 and 1 g of soil samples were used (obscuration: 5-20%); data conversion was performed by Mastersizer software (Mie theory). The optical settings were as follows; absorption index (AI) = 0.1, solid phase refractive index (RI) = 1.52, and water refractive index (RI) = 1.33. Limits of particle size fractions (PSF), *i.e.* clay/silt and silt/sand, were 7 and 50 μm, as proposed by Makó *et al.* (2019). Finally, the soil samples were classified into texture groups according to the USDA (12) texture triangle.

LDM PSD measurements were performed without preparation steps (destroying cementing, stabilizing agents) but using different combinations of pretreatments and liquid phases. The applied four pretreatment types included no treatment (T1), the use of only 27 cm^3 Calgon (T2) or

Table 3. Properties of the aqueous mediums (DW – distilled water and TW – tap water) used during LDM measurement

Code of liquids	Aqueous medium	pH	EC (μS cm^{-1})	Na$^+$	K$^+$	Ca^{2+}	Mg^{2+}	Total hardness (mg l^{-1} CaO)
				(ppm)				
DW	distilled water	6.4	2.2	0	0	0	0	0
TW	tap water	7.7	530	26	2.6	67	17	136

40 W/40 kHz ultrasound for 240 min (T3), and their combination (T4 – 27 cm^3 Calgon + 40 W/40 hHz ultrasound for 240 min). The Calgon solution was prepared according to the ISO 11277:2009(E) standard making a mixture of 33 g of Na-hexametaphosphate and 7 g of anhydrous Na-carbonate L^{-1}. Distilled water (DW) and tap water (TW) were used to test the effect of the aqueous medium on PSD and texture classification results (Table 3).

The combined effects of the measurement methods (SPM, LDM), soil samples, dispersion methods (T1-T4), and water quality (DW, TW) were investigated using GLM Univariate Analysis (UNIANOVA) on the complete measurement database. The distribution of variables was checked using the Shapiro-Wilk test. In the case of normal distribution, the independent t test was used to compare the treatments. If the variable was not normally distributed (this was usually the case), the Nonparametric Independent-Samples Mann-Whitney U test was used to compare the groups (IBM SPSS Statistics ver. 20).

Texture classified by various PSF (based on PSD in DW and TW) were plotted on USDA 12-category texture triangle diagrams using OriginPro version 2021 (OriginLab statistical software).

Confusion matrix classification accuracy analysis (Caret – Kuhn, 2008 and Psych – Revelle, 2011 in R ver. 3.4. – R Core Team, 2016) was used to compare the resulting USDA texture categories (Congalton and Green, 2008; Salley *et al.*, 2018) obtained from LD PSD, near the four pretreatments (T1-T4) in two different aqueous media (DW and TW), and PSD measured with the conventional SPM method. Overall accuracy values of confusion matrices (*OA*) refer to the absolute number of different treatments that match the texture classification results of the SPM results:

$$OA\ (\%) = 100\frac{\sum_{i=}^{r} E_{ii}}{N}, \tag{1}$$

where *r* is the number of texture classes, E_{ii} is correctly classified cases of a texture class, *N* is the number of measurements.

The Kappa (κ) value indicates the accuracy of texture classification, considering the probability of a random match/random misclassification, compared to the average of the SPM results:

$$\kappa = \frac{P_0 - Pe}{1 - Pe}, \tag{2}$$

where P_0 is the proportion of samples classified as the same as the SPM measurements and *Pe* is the probability of random agreement.

The value of Kappa (κ) can vary between -1 and 1, where values <0.0 indicate poor agreement, values 0.0-0.2 and 0.2-0.4 indicate slight and fair agreement, values 0.4-0.6 or 0.6-0.8 indicate moderate and substantial agreement, and finally values between 0.8 and 1.0 mean the agreement is significant, almost perfect.

Balanced accuracy (BA%) refers to the percentage of classification in a given texture group that corresponds to the texture classification determined by the SPM measurement (taking all observations/cases into account) (Congalton and Green, 2008; Salley *et al.*, 2018). Balanced accuracy is a performance metric used for imbalanced datasets where some classes appear more frequently than others. It ensures that each class contributes equally to the final metric. For each class, balanced accuracy is calculated as:

$$BA_i(\%) = 100\frac{Se_i + Sp_i}{2}, \tag{3}$$

where: Se_i is the "sensitivity/true positive rate" for class *i*:

$$Se_i = \frac{TP_i}{TP_i + FN_i}, \tag{4}$$

and Sp_i is the "specific/true negative rate" for class *i*:

$$Sp_i = \frac{TN_i}{TN_i + FP_i}, \tag{5}$$

where: TP_i – true positives correctly classified instances of class *i*; FN_i – false negatives instances of class *i* incorrectly classified as other classes; TN_i – true negatives all samples that are not class *i* and were correctly classified as not being class *i*; FP_i – false positives all samples that are not class *i* but were misclassified as class *i*.

3. RESULTS

3.1. Particle size fractions of investigated soil samples in various treatments

Particle size fractions (PSF) were measured with the sieve-pipette method (SPM) or the laser diffraction method (LDM). The mean PSF values and their standard deviations for each treatment of the complete measurement matrix are presented in Table 4. Univariate Analysis (UNIANOVA) showed a significant combined effect of pre-treatments (T1-T4) and pre-treatments and water quality (Sig.: 0.000 – not shown in the table) on PSF values. For the full measurement matrix (all soil samples), we could not demonstrate a significant effect of liquid quality on PSF values (Sig. 0.488-0.999 – not displayed in the table).

Table 4. Mean and standard deviation (σ) of the particle size fractions (Clay: < 0.002 mm; Silt: 0.002-0.05 mm and Sand: > 0.05 mm) determined by various methods after different preparation and pretreatments and liquid mediums

Liquid medium	PSD fractions	T1 (LDM)		T2 (LDM)		T3 (LDM)		T4 (LDM)		SPM	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
DW	Sand	56.32	21.58	27.84	13.63	25.83	15.81	28.04	15.52	29.83	22.66
	Silt	32.10	9.78	44.30	8.15	45.91	7.09	41.12	7.83	37.46	11.56
	Clay	11.58	14.22	27.86	11.98	28.26	14.75	30.84	9.04	32.71	15.07
TW	Sand	62.42	16.18	28.46	13.94	26.03	17.21	25.28	15.82	-	-
	Silt	30.98	11.54	44.76	8.71	45.92	6.67	41.03	7.60	-	-
	Clay	6.60	4.87	26.78	12.24	28.05	16.03	33.69	9.64	-	-
Sig.	Sand	**0.001**		0.719		0.626		0.950			
	Silt	0.207		0.063		**0.028**		0.107			
	Clay	**0.000**		0.280		0.127		0.970			

DW is distilled water; TW is tapwater; T1-T4 means the particle size distribution measurements with LDM after T1: no pretreatment, T2: pretreatment only with Calgon, T3: only with US and T4: combined treatment (Calgon+US); SPM means the particle size distribution measured according to the sieve-pipette method (ISO 11277:2009(E)) Sig.: results of statistical analysis of differences between SPM and LDM DW measurements (T1-T4) (Nonparametric Independent-Samples Mann-Whitney U test). Differences significant at the 95% confidence level are highlighted in bold.

Statistical comparisons (Nonparametric Independent-Samples Mann-Whitney U test) of distilled water (DW) SPM and LDM measurements (for all samples) are shown in the “Sig” values in Table 4. The results point to the combined effect of differences in aggregate binder removal (preparation procedures) and measurement methodology.

The particle size fractions (PSF) determined from the resulting LDM PSD measurement without pretreatment were the most distinct from the PSF determined from SPM PSD. The main reason for this may be that the results of the two types of measurements (with no or total pretreatment) can theoretically show the results of two “extremes”: texture classification after small dispersion between aggregates with a small physical effect and a texture classification determined after the complete disaggregation, complete removal of the binding agents between aggregates of the soils. The clay content in the SPM (measured after preparation steps) is generally higher than expected, while the sand content is lower than that determined by LDM, without preparation (since the complete preparation means the removal of $CaCO_3$, Fe-oxi/hydroxides, and organic matter responsible for aggregate formation). The results of PSF LDM measurements with chemical and/or physical dispersion are closer to the results of SPM.

The LDM PSF averages determined using different liquid phases do not differ significantly when all soils are considered together, which is due to the substantial standard deviation that may be observed. The marked standard deviations are explained by the variability of soil properties and probably by the different degree of interaction between the solid phase and the liquid phase in given environments, depending on soil properties. The differences between the standard deviations and the means clearly show the deviations between the results of the PSD measurements, depending on the liquid phase and the treatment methods applied. This may also be indicated by that the standard deviation of untreated samples is not always the largest (*e.g.* in the determination of clay content in the T2 and T3 treatments or clay content at DW or TW in T1).

3.2. Texture of soil samples (USDA 12 texture triangle)

The SPM method according to the ISO standard was considered as a reference; it was assumed that complete degradation of soil aggregates and complete dispersion of elementary particles had taken place in this case. The soil textures observed were sandy loam (S4), loam (S2, S3), sandy clay loam (S5), clay loam (S6), silty clay loam (S7), and silty clay (S1, S8) (Fig. 1). The differences in the measurement methods, aqueous media, and pretreatment may have resulted in deviations in the texture classification of the soil samples.

For most of the soil samples, the results of the laser diffraction measurements with the two aqueous media were almost similar (the measurement points overlapped in the diagrams – Fig. 1). In the case of T1, the LDM PSD measurements showed a predominance of coarser particle fractions in both aqueous media (DW, TW). A monotonically increasing trend of clay content, as a result of continued low disaggregation, was clearly observed in the point series. The identifiable soil texture categories were LoSa, SaLo, Lo, and SiLo. An exception was one sample with high clay content and high adsorbed sodium content (KAR). Here, DW gradually released clay particles also after the T1 (the exchangeable sodium ions adsorbed on the surface of the particles and “assisted” dispersion, disaggregation, and release of the clay fraction). The detectable soil texture in this sample was silty clay loam, silty clay, and clay.

At T2, it can be concluded that the chemical dispersant facilitated the disintegration of a significant part of the aggregates in the soils. The textures defined here were

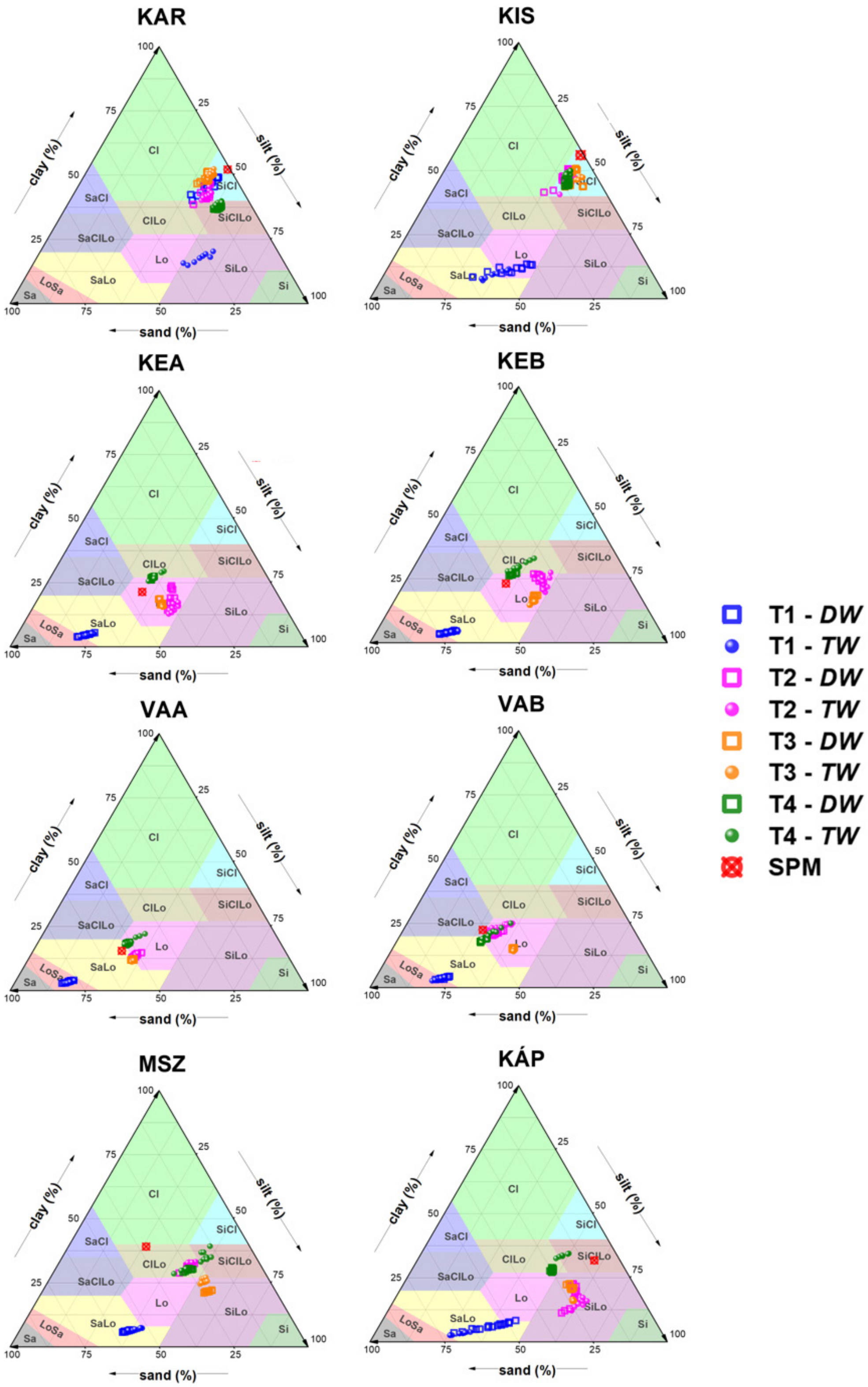


Fig. 1. Texture classifications according to the results of the LDM and SPM PSD measurements: pretreatment T1 – no pretreatment, T2 – pretreatment only with Calgon, T3 – only with US and T4 – combined treatment (Calgon+US); LDM refers to the results of the texture classification based on PSD data measured with laser diffraction method in distilled water (DW) and in tap water (TW); and SPM means texture classification data based on measurement with sieve-pipette method (ISO 11277:2009(E)). The texture classes are: Sa – sand, LoSa – loamy sand, SaLo – sandy loam, Lo – loam, SiLo – silt loam, Si – silt, SaClLo – sandy clay loam, ClLo – clay loam, SiClLo – silty clay loam, SaCl – sandy clay, SiCl – silty clay, Cl – clay.

SaLo, Lo, ClLo, SiLo, SiClLo, SiCl, and Cl. It can be seen that the samples were highly scattered by soil texture class, compared to the previous treatment. Differences could also be seen between the results of the measurements with different liquids.

Significant scattering by soil texture was also observed for T3 although the scattering pattern was slightly different from that observed for T2. The standard deviation between the parallel measurements of individual samples was smaller in T3 than in T2 (more overlap of points, fewer points). The identifiable soil textures were SaLo, Lo, ClLo, SiLo, SiClLo, SiCl, and Cl (similar to T2).

The texture triangle of T4 showed the strongest dispersing effect (the measured clay content is generally the highest here). This was reported by Tan *et al.* (2017) as well. The soil texture scatter plot was the most consistent in this case. The replicates of the measurements for each sample were also the least different (overlapping points). The smallest differences were found between the soil textures determined for the various aqueous media. The soil textures were similar to T2-T3, except that within each texture class, the samples "slipped" towards higher clay content (SaLo, Lo, ClLo, SiLo, SiClLo, SiCl and Cl).

3.3. Texture classification (confusion matrices)

The texture classification based on the LDM T4 results seemed to be most similar to the classification based on the SPM reference measurements (Table 4 and Fig. 1), as also reported by Polakowski *et al.*, 2023). However, the summary statistics of the confusion matrices (Table 6) do not show this. Based on the overall accuracy (OA) and Kappa (κ) values, the texture categories of the LDM T3 measurements showed the best agreement (moderate or substantial) with the SPM measurements in both aqueous media. However, the categories based on the LDM T4 measurements showed only the 3rd best agreement (slight or fair). According to Shein *et al.* (2006) and Tan *et al.* (2017), it is not always sufficient to use only one procedure (dispersant or US). The poorest agreement was found for T1 (poor or slight).

According to the summary table (Table 5), the best agreement was found for the TW T3 combination. However, for the T4 measurements, the texture categories defined in DW showed higher similarity to the SPM categories than TW. It can also be concluded that the extent of the deviation from the reference categories is more influenced by the pretreatments than by the quality of the aqueous media.

In addition, OA and κ values (Table 5) are statistically informative but insufficient indicators if we want to know practically the amount of "misclassification". Thus, the balanced accuracy (BA) calculated for each texture group is shown in Table 6 (for DW and TW). These tables also include the percentage of misclassifications relative to the texture class based on the reference measurement results. The texture classes of the confusion matrices can be well identified for each soil sample so that the behaviour of each soil sample in different aqueous media under different pretreatments can be well studied in terms of texture classifications by knowing the soil properties (Table 6).

Table 5. Confusion matrix analysis. Changes in overall accuracy (OA) and Kappa (κ) values for different treatments and aqueous media compared to the texture classes obtained from LDM and SPM PSD data

Pretreatment	Aqueous media			
	LDM DW ↔ SPM		LDM TW ↔ SPM	
	OA%	κ	OA%	κ
T1	13.1	0.008	0.0	-0.090
T2	60.7	0.522	63.9	0.550
T3	63.0	0.547	69.1	0.609
T4	43.0	0.306	35.8	0.228

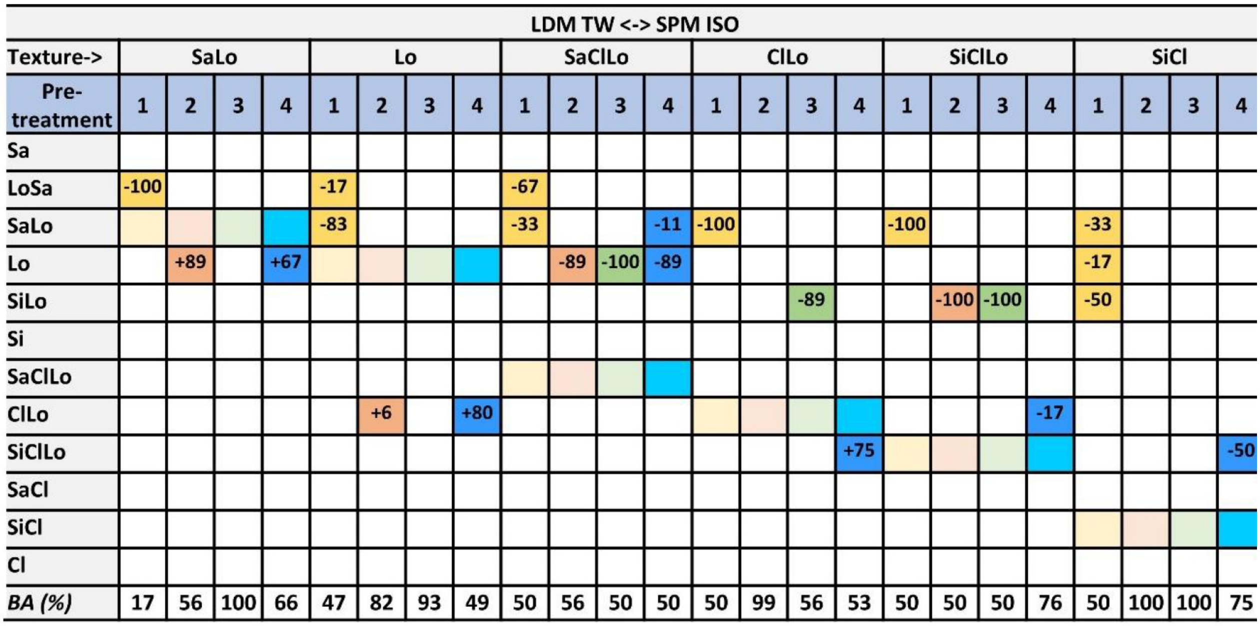
Pretreatment T1 – no pretreatment, T2 – pretreatment only with Calgon; T3 – only with US and T4 – combined treatment (Calgon+US); LDM refers to the results of the texture classification based on PSD data measured with laser diffraction method in distilled water (DW) and in tap water (TW); and SPM means texture classification data based on measurement with sieve-pipette method (ISO 11277:2009(E)).

This is reflected in the SPM↔LDM texture shifts, the magnitude of which can vary between texture classes and aqueous media. However, the results clearly showed very low disaggregation in the LDM T1 measurements (BA values were also the lowest here). The distance between the SPM and LDM T1 texture classification was increased towards the finer textured classes (sandy loam → silty clay), presumably due to the higher aggregate stability of the finer textured soils.

An exception was the silty clay (SiCl) class, which included a sample with higher aggregate stability (KIS) and a sample with very poor stability and high Na^+ content (KAR). It could be seen from the tables that here the LDM T1 texture classes of the KAR samples for DW were approximately the same as the SPM classes, and texture determined by the PSD results measured in TW liquid medium showed the largest deviation from the SPM classes (which in this case also illustrates that flocculation probably also took place in the KAR sample due to the high calcium salt content in the tap water).

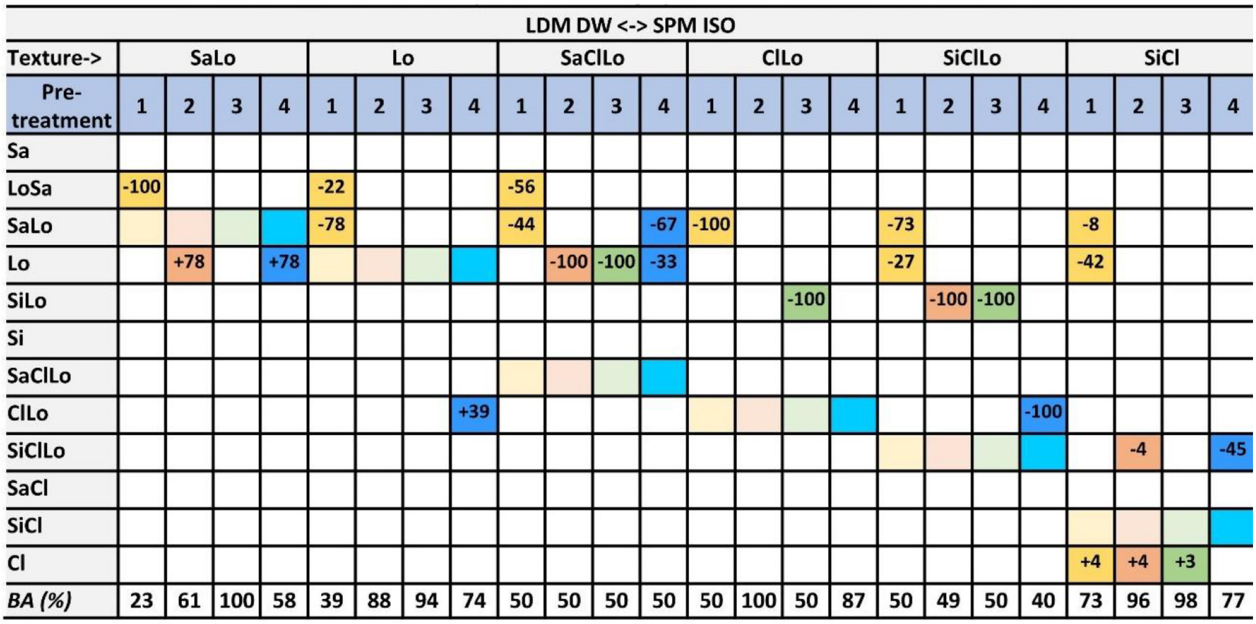
In the case of the other pretreatments (T2-T4), both positive (finer texture) and negative (coarser texture) shifts in the LDM measurements compared to the SPM measurements were observed. For measurements in DW media, the shifts were more in the negative direction, indicating that the LDM T2-T4 pretreatments were generally not able to fully degrade the aggregates, but only resulted in partial disaggregation. The extent of partial disaggregation varied between treatments and soil types. Most disaggregation

Table 6. Confusion matrix analysis; texture category matches between texture classification based on laser diffraction PSD measurement in tap water (top) or in distilled water (bottom) and the sieve-pipette method according to the ISO 11277:2009(E) standard (LDM TW ↔ SPM ISO; LDM DW ↔ SPM ISO)



LDM TW <-> SPM ISO

Texture->	SaLo				Lo				SaClLo				ClLo				SiClLo				SiCl			
Pre-treatment	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Sa																								
LoSa	-100				-17				-67															
SaLo	🟨	🟧	🟩	🟦	-83				-33			-11	-100				-100				-33			
Lo		+89		+67	🟨	🟧	🟩	🟦		-89	-100	-89									-17			
SiLo															-89			-100	-100		-50			
Si																								
SaClLo									🟨	🟧	🟩	🟦												
ClLo						+6		+80					🟨	🟧	🟩	🟦				-17				
SiClLo																+75	🟨	🟧	🟩	🟦				-50
SaCl																								
SiCl																					🟨	🟧	🟩	🟦
Cl																								
BA (%)	17	56	100	66	47	82	93	49	50	56	50	50	50	99	56	53	50	50	50	76	50	100	100	75



LDM DW <-> SPM ISO

Texture->	SaLo				Lo				SaClLo				ClLo				SiClLo				SiCl			
Pre-treatment	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Sa																								
LoSa	-100				-22				-56															
SaLo	🟨	🟧	🟩	🟦	-78				-44			-67	-100				-73				-8			
Lo		+78		+78	🟨	🟧	🟩	🟦		-100	-100	-33					-27				-42			
SiLo															-100			-100	-100					
Si																								
SaClLo									🟨	🟧	🟩	🟦												
ClLo								+39					🟨	🟧	🟩	🟦				-100				
SiClLo																	🟨	🟧	🟩	🟦		-4		-45
SaCl																								
SiCl																					🟨	🟧	🟩	🟦
Cl																					+4	+4	+3	
BA (%)	23	61	100	58	39	88	94	74	50	50	50	50	50	100	50	87	50	49	50	40	73	96	98	77

The coloured fields show the reference classification, while the same coloured but darker fields show the percentage of observations misclassified. Positive percentages indicate a shift towards a finer texture category and negative values indicate a shift towards a coarser texture. The detailed balanced accuracy (BA) values for texture classes are informative as to which pretreatment provides more or less accurate LDM PSD results in which texture categories. The texture classes as in Fig. 1.

Table 7. Mean particle size fractions, their changes and the direction of the changes according to the applied fluid medium (DW→TW)

Code	KAR		KIS		KEA		KEB		VAA		VAB		MSZ		KÁP	
Type	Solonetz		Vertisol		Cambisol				Luvisol				Luvisol		Chernozem	
Sand	11.2 27.1 ↑	9.7 7.1 ↓	46.8 53.3 ↑	7.4 5.7 ↓	72.3 71.6 ~	40.8 40.8 ~	71.6 71.7 ~	35.7 37.2 ↑	78.8 78.2 ~	52.8 53.0 ~	73.5 75.0 ~	44.2 44.7 ↑	57.7 54.2 ↓	22.8 22.3 ~	56.6 68.2 ↑	21.8 23.5 ↑
	13.4 12.3 ~	11.7 10.3 ↓	11.3 9.5 ~	10.9 9.4 ↓	36.5 37.0 ~	38.9 37.2 ~	30.5 29.3 ~	38.8 34.5 ↓	50.9 50.9 ~	51.4 49.7 ~	46.6 43.6 ↓	53.0 47.6 ↓	24.7 22.8 ↓	25.1 19.5 ↓	22.7 22.3 ~	24.8 18.3 ↓
Silt	43.3 55.0 ↑	41.2 42.4 ↑	41.7 37.2 ↓	45.2 47.1 ↑	23.1 23.8 ~	41.9 43.4 ↑	24.3 24.3 ~	46.5 47.2 ↑	17.7 18.4 ~	35.1 35.4 ~	22.8 21.5 ~	40.5 41.1 ↑	36.1 38.9 ↑	55.6 52.0 ↓	37.4 28.5 ↓	56.8 60.3 ↑
	44.5 44.8 ~	51.1 50.7 ~	41.3 43.6 ↑	44.0 42.1 ↓	44.5 47.4 ↑	34.3 35.3 ↑	44.6 47.2 ↑	34.6 35.4 ~	35.3 35.3 ~	30.2 31.0 ~	32.2 32.4 ~	28.8 30.8 ↑	44.2 44.5 ~	44.8 46.5 ~	58.9 62.9 ↑	47.3 48.0 ~
Clay	45.5 17.9 ↓	49.1 50.5 ~	11.5 9.5 ↓	47.5 47.1 ~	4.6 4.6 ~	17.3 15.8 ↓	4.1 3.8 ~	17.9 15.6 ↓	3.5 3.4 ~	12.1 11.6 ↓	3.7 3.5 ~	15.3 14.2 ↓	6.2 6.9 ↑	21.6 25.7 ↑	6.0 3.2 ↓	21.4 16.2 ↓
	42.1 43.0 ~	37.2 39.0 ↑	47.4 46.9 ~	45.0 48.6 ↑	19.0 15.6 ↓	26.8 27.6 ~	24.9 23.5 ~	26.7 30.1 ↑	13.8 13.8 ~	18.4 19.3 ~	21.2 24.0 ↑	18.3 21.7 ↑	31.1 32.7 ↑	30.0 34.0 ↑	18.4 14.8 ↓	27.9 33.6 ↑

Numbers written in italics are the results of LDM measurements in tap water and numbers in normal font are the mean of soil fractions measured with LDM in distilled water. Colours refers to the types of pretreatment: T1 – no pretreatment (white), T2 – pretreatment only with Calgon (blue-grey), T3 – only with US (orange) and T4 – combined treatment (Calgon+US – green); ↑ and ↓ means significant increase or decrease in the fraction if there is tap water (TW) used as liquid medium instead of distilled water (DW); ~ means that no significant difference between PSF values measured with different liquids, according to Nonparametric Independent-Samples Mann-Whitney U Test.

occurred in Lo textured soils (KEA and KEB), presumably due to the poor aggregate stability of KEA and KEB Cambisol soils. This might also be explained by BA values, which refer to the best match between SPM – LDM textures (Tables 6 and 7).

A similar result was observed for the A horizon of Luvisol soils (VAA, sandy loam), where a positive texture class shift occurred in T2 and T4, but not to a very significant extent (sandy loam → loam). This is probably due to the differences in measurement methods and the fact that the sand fraction in high sand content soils is often somewhat underestimated by LDM methods (depending on the design of the preparation unit) (Sochan *et al.,* 2012; Polakowski *et al.,* 2015; Mattheus *et al.,* 2020; Stevenson *et al.,* 2023).

Similar reasons may also be responsible for the loam → clay loam bias in some cases in the T4 pretreatment. The smallest disaggregation (the largest SPM↔LDM divergence) was observed for the accumulation zone (SaClLo: VAB) of Luvisol soils and the upper humic layer (SiClLo: KAP) of Chernozem soils (negative reclassification values – Table 6), which can also be explained by the higher aggregate stability (related to higher organic matter and/or iron content) of the samples.

Good soil texture agreement was also observed between SPM and LDM in the gleyic Luvisol soil B horizon (ClLo: MSZ) for the T2 and T4 pretreatments. The aggregate stability of this soil was less influenced by organic matter or Ca-carbonate content, thus the aggregate composition is presumably mainly determined by the interactions between Fe-oxy/hydroxides and clay minerals, which provide a high specific surface area. A texture with slightly lower clay content was determined for T3. It seems that for this soil, the chemical dispersing effect of Calgon is absolutely necessary during LDM measurements; otherwise, its particles will clump and flocculate.

The situation is slightly different for silty clay (KAR and KIS) soils, where the T2 and T3 pretreatments gave good agreement (one or two measurements only cause a slight under- or overestimation, which could be a measurement error). The overestimation of the clay content in the LDM may also be due to the fact that, in the SPM ISO measurements, the loss of the clay fraction may be caused by the overflow of the supernatant after the removal of the adhesive during chemical preparation (Balázs *et al.,* 2011; Makó *et al*., 2019). However, in the case of T4, flocculation was observed in this texture in the KAR soil due to Calgon + US (see above), which caused a decrease in clay content and texture change (silty clay → silty clay loam) (as in TW). For the T1 treatments, a lack of disaggregation was observed in all the samples except for KAR. For the T2-T4 treatments, the SPM measurements indicated that the SaLo (VAA) textured soil grades to finer textures in both two fluids (positive signs). Similarly, for the Lo texture, positive reclassifications were also observed in TW and also in DW liquid media.

The soils with high aggregate stability (SaClLo: VAB and SiClLo: KAP) also showed only partial disaggregation in the LDM measurements in any liquid (negative sign for the reclassifications), but the effect of the pretreatments on texture reclassifications also varied between the aqueous media. The SPM↔LDM agreement for the ClLo (MSZ) textured soil was relatively as good in the case of DW as in the case of the TW liquid media used. In the SiCl textured soils (KAR and KIS), a slightly more mixed picture was found. In soils with high clay content and/or high Na^+ content, it seems that the quality of the aqueous media plays a more important role in the LDM measurements than in the previous soils. Here, for the T2 and T3 pretreatments, a complete SPM - LDM texture match was observed for TW, while the extent of texture misclassification for T4 was slightly smaller in the case of the DW medium.

It is important for the generalisability of the results that none of the samples can be classified as a sand size fraction, and only after enormous treatment can some samples be classified as clay. Furthermore, our results do not provide information about soils with silt, sandy loam, and sandy clay texture categories. In terms of soil properties, our soils are also not representative of soils with high carbonate content, high organic matter content, *etc*. However, it is reasonable to conclude that the texture classification is significantly influenced by the measurement and preparation procedure, since in all cases a certain percentage of reclassification is observed (BA% for DW 23-98% and for TW 17-100%; in more than 50% of cases, more than two categories are "jumped").

4. DISCUSSION

4.1. Differences in PSF according to the applied liquid media

Smaller dispersibility was observed in the PSF values (Table 7) determined in tap water, without treatment, especially in the case of the soil KAR – Solonetz, with higher salt content. In this case, it is possible that Ca-carbonates and phosphates (from Calgon and from water) form a precipitate in the system near a high sodium content (Shein *et al.*, 2006), but it is also possible that the greater ionic exchange due to the high CEC of the sample makes some aggregates more resistant (Mason *et al.,* 2011; Tan *et al.,* 2017). However, in the case of *e.g.* soils with higher illite and Mg content, there was also a stronger dispersion effect of TW in some pretreatments. This dichotomy was also observed in the texture classifications of the untreated and Calgon-only treated samples (T1-T2). The measurement in distilled water gave a more similar (even if slightly similar) classification to the SPM method, while for T3 and T4, the classification based on PSF determined in TW gave better results.

In the case of the LDM T1 measurement, the samples generally had lower disaggregation and dispersion (higher sand content) degrees in TW compared to DW (except Cambisols and Luvisol *e.g.* VAA – Table 2). This might be explained by ion exchange processes due to the higher Ca-carbonate content in tap water (hard water, 13.6 dH CaO mg/L), which might lead to higher aggregate stability (even if only temporarily) against lower dispersive forces (Tan *et al.,* 2017). It is also possible that the smaller particles produced in the initial disaggregation steps are temporarily adsorbed (physically rather than chemically) on the surface of the medium sized particles (Shein *et al.,* 2006; Tan *et al.,* 2017).

According to Murray (2002), TW can contribute to higher resistance to weak dispersion, as Ca^{2+} ions can enhance the aggregate-protective effect of various organic substances and/or clay films. Later, when the samples are treated with Calgon, the weakly bound fine-fraction coating on the surface is eliminated, reducing the average particle size (Murray, 2002; Goossens *et al.,* 2014). However, aggregates and elementary particles are explicitly difficult to separate (Totsche *et al.,* 2018), because different and varying degrees of interactions can occur between particles in different size ranges.

When the samples were dispersed with Calgon only or US only, no significant differences in the PSF values were observed according to the quality of the liquid media. In general, higher clay content was found with DW, except for KEA – Cambisol, which had higher clay content in DW, while VAB – Luvisol and MSZ – Luvisol had higher clay content with the use of TW. The dispersing effect of Calgon (Na^+), according to its chemical mechanism of action, can be significantly determined by the properties of the soil-liquid medium-dispersant, such as Ca/Mg salts and bicarbonates, Na and total salt content, or even by the pH increase that occurs with the addition of the dispersant (in our measured medium, pH 9.61-10.3 for TW and DW), as mentioned in the literature (Rengasamy *et al.,* 1984; Li *et al.,* 2023).

A better dispersion effect with TW was found for a sample with medium CEC (but high Mg content in the exchangeable sites), high clay and Fe-oxide/hydroxide content (MSZ – Luvisol), for almost all the pretreatments. On the contrary, for the more alkaline soil (KÁP – Chernozem) with better aggregate stability, good structure, and higher organic matter content, the dispersion in TW was reduced, as well as for KIS, KAR, and KEA, which also had higher humus content. Thus, due to its Ca/Mg content and "higher salinity", TW may not only be a dispersing or flocculating agent, but depending on the ionic composition of the medium, precipitation or even co-precipitation with the Calgon dispersant may also occur during pretreatment and measurement (Murray, 2002).

Furthermore, both too little and too much Calgon (what is considered excessive depends on the soil properties) can lead to erroneous measurements (artefact formation or insufficient dispersion, higher scattering, *etc.* – even in hydrometer measurements) (Kaiser *et al.,* 2012; Kaur and Fanourakis, 2018; Murray, 2002). It might simplify the issue if it were possible to suggest the amount of Calgon added to different soil samples according to the chemical composition of the tap water (optimum value is around 4% in the literature mentioned above, and roughly this concentration was used in our studies).

An interesting finding is the higher dispersion of the KIS – Vertisol with high clay and humus content in TW at the Calgon and T4 treatments (as opposed to no treatment) despite its higher aggregate stability. This might be explained by the mineral composition of clay, *e.g.* if soils contain more dispersible illite (Goossens *et al.,* 2014). The effect of mineral quality on chemical dispersion rates has been observed in their PSD measurements by Polakowski *et al.* (2023) and Tan *et al.* (2017).

It is also noteworthy that the KEA and KEB – Luvisol with medium aggregate stability showed higher silt content in the T2 treatment due to the effect of the excess calcium carbonate content in TW than DW; also KÁP – Chernozem exhibited higher silt content in both T2 and T3 treatments due to TW. According to Abdulkarim *et al.* (2021), incomplete dispersion might first lead to the formation of smaller "precipitates" (small aggregates, particles formed naturally and by treatment), which might reaggregate between larger particles or form coatings on them, thus increasing the silt content. However, the higher level of dispersion in the combined treatment was generally observed in the LDM measurement in TW, which is somewhat surprising in view of the previous results. It was therefore concluded that different disaggregating forces may occur or prevail depending on the pretreatment if the ionic composition and ionic strength of the liquid used are different. The fact that the change in the clay content with the application of TW is in the opposite direction in the T4 combined treatment compared to the T3 and T2 treatments shows that the effects of chemical and mechanical dispersion may not be merely additive but synergic. Chemical and physical effects of pretreatments can "reinforce" or even "weaken" each other.

4.2. Differences in PSF according to the applied pretreatment method and soil type

According to our results, preparation and pretreatment procedures also vary in their effectiveness. For all samples, the difference in the effect of pretreatment was most significant between untreated and pretreated samples. A particularly significant difference between PSFs measured for the various liquid phases used was observed for the KAR – Solonetz sample with high clay and Na^+ content if no pretreatment had been applied. The difference between T1 and T2-4 was smaller for the KAR samples, where the high Na^+ content may have led to a significant spontaneous and rapid disaggregation effect (reference) in all the three treatments. However, dispersion effects of salts may be influenced by not only the effects of charge but also the concentrations and rate of ions (concentration effect – Filep, 1999). Thus, the question may arise as to the suitability of tap water for measurements of *e.g.* high salinity or dispersive (high Na^+; Mg^{2+}) samples if the purpose of the study requires that a texture corresponding to the "in situ" measurable particle size distribution is determined in the laboratory (*e.g.* Goossens *et al.,* 2014; Martín *et al.,* 2018). Similar rapid dispersion of aggregates was found in DW depending on other properties of the medium (total salt content, pH, *etc.*) by Goossens *et al.* (2014) investigating the particle size distribution of sulphate and carbonate soils of arid regions. According to the authors, the use of a less dispersive medium for measurements (*e.g.* isopropyl alcohol) should be considered when PSD values closer to natural ones are required (*e.g.* erosion modelling) for dispersive soils.

The disaggregation of the KAR sample was significantly different from the other soil samples, thus it can be characterised by a different disaggregation pattern. In the US (T3) treatment, the lower sand content was measured by using TW only in this case. Furthermore, in the combined treatment (T4), a decrease in the clay fraction and a parallel increase in the silt fraction were observed, since the dispersing effect of Calgon (repulsive effect of increasing Na^+ content; complexing ability of NaHMP; increasing the pH of the suspension and reducing positively charged surfaces) depends on the proportion of Na^+ present and able to act in the suspension (Kaur and Fanourakis, 2018). The silt content was higher in this case compared to both the treatments with only US (T3) or Calgon (T2), suggesting that flocculation or aggregation processes may occur when the two treatments are used together in the presence of high Na^+ in the samples.

In the KIS – Vertisol, the KEB – Cambisol, and the VAB – Luvisol samples, even a small significant "increase" in the sand content was observed in the results of the combined treatment (T4), compared to the results of the T2 (Calgon) treatment. According to Mason *et al.* (2011), in less dispersive soils (with lower Na^+ and/or Mg^{2+} content), the sand fraction can also change positively in response to treatments.

The results of the LDM measurements showed a small but typical change in the silt and/or clay fraction between treatments with dispersing effects (except for the MSZ – *Luvisol* sample), probably as a result of further dispersion of smaller macro- and microaggregates to different extents. It varies by soil type which of the treatments with only one dispersing effect (T2-3) results in more efficient dispersion.

In the combined treatment, the higher silt content may also have resulted from the formation of possible crystalline and/or amorphous Ca phosphate precipitates from the components of the liquid (*e.g.* in TW) and dispersing agents not only from the soil-dispersing agent interaction (Buurman *et al.,* 1997; Mason *et al.,* 2011). This may also be the reason why the results of the confusion matrix showed that the T3 treatment gave a better approximation to the texture values determined from the SPM measurements.

For the T2 (Calgon) treatment, the effect of liquid phases on the PSF values was less pronounced than for the T3 (US) treatment. However, the standard deviation of the PSF values measured by Calgon was generally larger than was the case of the use of only US, which may be a consequence of the fact that the chemical reactions caused by the dispersant may operate through more complex mechanisms than the mainly mechanical action of the US. In general, the deviation between the results of the T2 and T3 measurements is assumed to be larger if the aggregate stability of the samples is achieved by multiple and more significant cohesive and binding aggregation forces. These disaggregation steps are determined primarily by the aggregate constituents of the soil (by their size distribution and quality) and the degree of binding forces between them (Amézketa, 1999; Bronick and Lal, 2005; Totsche *et al.,* 2018). Such "stepwise disaggregation" was observed to a lesser extent in KEA – Cambisol and VAA – Luvisol from MSZ (Luvisol) and clearly in the KÁP – Chernozem samples characterised by the best soil structure.

The cyclical disaggregation in successive steps (spontaneous or forced dispersion, disaggregation, dissolution of humus coatings, soluble components, *etc*.) of organomineral complexes and different sized aggregates, typical of well-structured soils, is most pronounced in Chernozem samples (Shein *et al.,* 2006; Bartmiński *et al*., 2022; Gresina *et al.,* 2025). This was also evidenced by the marked difference between the T4 and other treatments. It is questionable, however, whether full disaggregation can be achieved without the preparation procedures, as lower silt content or higher sand content was measured with the LDM compared to the silt content determined with the SPM method, even with the combined pretreatment. This may also have resulted from the difference between the two types of measurements (including different preparation methods). Based on the literature, the difference between PSD measurements by LDM and SPM tends to affect the clay and sand fractions in general, with less noticeable differences in the silt fraction (even when appropriate size limit values are assigned) (Yang *et al.,* 2015; Makó *et al.,* 2017; 2019; Sitzia *et al.,* 2017). On the contrary, the silt fraction of Chernozem samples varies with the effect of different treatments (and also with the addition of TW). Shein *et al.* (2006) and Tyugai *et al.* (2010) also found the partial disintegration of Chernozem soil samples after US pretreatment and concluded that chemical disaggregation is at least as important as mechanical disaggregation in well-aggregated soils.

Nevertheless, the use of US also has a chemical effect, as it increases the dissociation rate and thus the pH of the sample, affecting the efficiency of dispersion (Matouq, 2008). Different levels/strengths and durations (sum of forces) of US treatment can be used to disintegrate particles from aggregates formed by different binding forces in physicochemical processes (changing *e.g.* pH, heat and mechanical forces); Hence, the US treatment can be used to study the disintegration process of soils and sediments, quantifying aggregate stability (Fristensky and Grismer, 2008; Mason *et al.,* 2011).

Incomplete disaggregation was also shown in the case of the MSZ – Luvisol samples at all dispersing effects (including the effect of the Ca^{2+} content in the tap water). In addition to the medium macroaggregate stability (Table 1), these soils are more likely to be dominated by the role of microaggregate stability, which may be more resistant to dispersive effects. This phenomenon is probably explained by the presence of significant amounts of Fe-oxy/hydroxides and iron-humate complexes forming "composite building units", and mainly small microaggregates (Totsche *et al.,* 2018), and their continuous, force-dependent disaggregation (Kögel-Knabner *et al.,* 2008; Kaiser *et al.,* 2011; Regelink *et al.,* 2013; Kirsten *et al.,* 2021). Further investigation is needed in this direction because microaggregates behave differently in terms of various chemical/physical effects and different disaggregation strengths than macroaggregates (Bronick and Lal, 2005; Amézketa, 1999; Totsche *et al.,* 2018).

High microaggregate stability may prevail in both clay and silt fractions (by coupling of associates and microaggregates – Totsche *et al.,* 2018). The role of microaggregate stability is further highlighted by the fact that the fine silt fraction and clay fraction contain significant organic matter content (up to 50% – Shein *et al.,* 2006; Kirsten *et al.,* 2021). Probably, in this case, the difference between the results of the T4 LDM and SPM measurement reflects the effectiveness of Fe-oxide/hydroxide removal (washing with citrate-dithionite-bicarbonate) applied to SPM and the important role of iron in the aggregate stability of soils with high Fe-oxide content, such as forest soils. Moreover, the MSZ – Luvisol and KAR – Solonetz samples contained more swelling minerals, which might lead to susceptibility of these soils to disaggregation forces. The higher Na and/or Mg content might enhance the effect of swelling and fragmentation (Rengasamy *et al.,* 1984; Amézketa, 1999).

5. CONCLUSIONS

Results of PSF determination and texture classification may vary with the PSD measurement method (sieve-pipette or laser diffraction), the type of preparation (with or without the removal of aggregates, cementing agents), pretreatment, and the quality of the aqueous media applied during measurement. The amount of these deviations depends on the physical, chemical, and mineralogical properties of soils (*e.g.* aggregate stability, salinity, exchangeable Na^+, organic matter, Fe-oxy/hydroxides and clay content, CEC, mineral composition). Soils show different disaggregation patterns according to the soil/solid phase-fluid-dispersant interactions (cohesion, aggregation-dispersion, precipitation-dissolution, flocculation, ion exchange, competitions between ions, *etc*.). All these effects can reinforce or weaken each other (*e.g.* the effect of clay content on aggregate stability or resistance against dispersion, disaggregation depending on mineral quality, or a variable impact of the quality, ratio, and concentration of salts). Our study presents the results of investigations on various soil types, mostly found in many countries around the world. Although the number of elements is small, it may reflect the importance of the different degrees of correspondence between the results of texture classification using various methods when different soil types are investigated.

A universally acceptable pretreatment protocol appropriate to various soil properties has not yet been developed and is not advocated, as it is assumed that it would make PSF and texture determination too complicated and time-consuming. However, even the combined (Calgon+US) treatment did not provide full dispersion and disaggregation in all soils compared to the results obtained with the conventional sieve pipette method after total removal of binding agents (because of partial dispersion and the formerly mentioned interactions). Partial dispersion reduces the accuracy and reproducibility of the measurement, increases its uncertainty, and affects the result of the texture classification. Which pretreatment is more effective depends on soil properties. Nevertheless, it should be taken into account that the chemical composition of tap water may also vary. Depending on its composition (*e.g.* through higher hardness, Na^+ content, salinity, or ionic strength), it may cause flocculation/precipitation (Shein *et al.,* 2006) or facilitate precipitation of the fine fraction (Abdulkarim *et al.,* 2021), precipitate as artefacts (phosphate and carbonate), reaggregate (*e.g.* through cation exchange – Mason *et al.,* 2011), or can increase (even if only temporarily) aggregate stability and cohesive forces (through OM and clay coatings, complex formation – Murray, 2002; Goossens *et al.,* 2014; Tan *et al.,* 2017).

Misclassification of texture was found in more than half of the samples, which might lead to enormous error in hydrological modelling (Richer-de-Forges *et al.,* 2024). The question therefore remains of which pretreatment procedure would be appropriate and robust enough for application to agricultural soils, sediments, and geological media. Thus, the need for harmonisation of LDM measurement methods, including pretreatment types and steps, procedures, and the quality of the liquid to be used for the LDM measurement has been highlighted.

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