



Development of novel assessments for indoor air quality monitoring and impact on children's health

Project Details

Project Title	Development of Novel Assessments for indoor air quality monitoring and impact on children's health
Project Acronym	LEARN
Grant Agreement Number	101057510
Call	HORIZON-HLTH-2021-ENVHLTH-02
Starting date of the project	01/05/2022
Project Duration	48 months

The LEARN Consortium

Number	Role	Short name	Legal name	Country
1	COO	INL	International Iberian Nanotechnology Laboratory	PT
2	BEN	VUB	Vrije Universiteit Brussel	BE
3	BEN	ENV	Envirometrics Teknikoi Symvouloi Anonymi Etaireia	EL
4	BEN	KUL	Katholieke Universiteit Leuven	BE
5	BEN	UH	Universiteit Hasselt	BE
6	BEN	M&H	Mann + Hummel GmbH	DE
7	BEN	NIA	Nanotechnology Industries Association	BE
8	BEN	IMEC-NL	Stichting IMEC Nederland	NL
9	BEN	AU	Aarhus Universitet	DK
10	BEN	FI	F. Iniciativas Espana I Mas D Mas I SLU	ES
11	AP	AL	AlveoliX AG	CH
12	BEN	TU/e	Technische Universiteit Eindhoven	NL

Project aim

LEARNing about the status of air quality in schools and its impact on the cognition of children is a major cornerstone in LEARN. For that, we want to overcome the barriers

of the currently existing technologies and take a bold step towards developing and deploying novel sensors to detect the presence of possibly harmful air pollutants such as volatile organic compounds and ultrafine particles.

We will measure and characterize indoor and outdoor air pollutants and evaluate the presence of biomarkers of exposure and their effect on children's cognition while trying to recapitulate those effects using *C.elegans* as a biosensor. Moreover, we will use advanced human-based in vitro models of lung and skin coupled with a revolutionary multi-sensing device to investigate their mechanisms of toxicity in real time.

Novel remediation strategies will be explored to improve air quality and promote children's quality of life and life expectancy. The scientific achievements expected to result from LEARN will unlock a large technology potential in IAQ for decades to come, leading to disruptive societal and economic impacts steaming from a radical improvement in the quality of life of children in Europe. Project LEARN is part of the European indoor air quality and health cluster IDEAL

Document Details

Deliverable Type	Report
Deliverable N°	D4.6
Deliverable Title	Final Validation Report
Name of Lead Partners for this deliverable	INL, TU/e
Version	V.1.0
Contractual delivery date	30 Apr 2026
Actual delivery date	12 May 2026
Dissemination Level	PU

Revision History

The following table describes the main changes done in the document since it was created

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
V.0.1	May 7, 2026	Initial version INL, awaiting content from TU/e	INL
V.0.2	May 8, 2026	Included TU/e UFP content	TU/e
V1.0	May 12, 2026	Final version	INL & TU/e

Disclaimer

THIS DOCUMENT IS PROVIDED "AS IS" WITH NO WARRANTIES WHATSOEVER, INCLUDING ANY WARRANTY OF MERCHANTABILITY, NON-INFRINGEMENT, FITNESS FOR ANY PARTICULAR PURPOSE, OR ANY WARRANTY OTHERWISE ARISING OUT OF ANY PROPOSAL, SPECIFICATION, OR SAMPLE. Any liability, including liability for infringement of any proprietary rights, relating to the use of information in this document is disclaimed. No license, express or implied, by estoppels or otherwise, to any intellectual property rights are granted herein. The members of the project Learn do not accept any liability for actions or omissions of Learn members or third parties and disclaim any obligation to enforce the use of this document. This document is subject to change without notice.

"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them".

Table of contents

Project Details.....	1
The LEARN Consortium.....	1
Project aim.....	1
Document Details.....	2
Revision History.....	2
Disclaimer	3
Table of contents.....	4
1 Introduction and Context.....	5
2 INL Volatile Organic Compound (VOC) Sensor.....	6
2.1 Introduction Field Validation VOCs	6
2.2 Experimental Methods Field Validation	7
2.2.1 Photoionization signal acquisition	7
2.3 Results Field Validation	9
2.3.1 VOC Prototype Signal Response	9
2.3.2 Active Sampling and Reference Analysis Results.....	11
2.4 Conclusions	16
3 TU/e Ultrafine Particle (UFP) Sensor	17
3.1 Overview and rationale.....	17
3.2 Stage 1 — Capture of UFPs	18
3.2.1 Inertial impaction into a droplet.....	18
3.2.2 Electrostatic delivery — simulation.....	19
3.2.3 Alternative — UFP capture on a solid surface	20
3.3 Stage 2 — Droplet handling on the PCB.....	21
3.3.1 EWOD on glass — reference validation	21
3.3.2 Practical implementation of EWOD on PCB	21
3.3.3 Dielectrophoretic (DEP) actuation as a complementary variant	21
3.4 Stage 3 — Single-particle detection by the fiber-tip PhCC sensor.....	22
3.4.1 Sensor architecture and read-out	22
3.4.2 Concentration-series measurements.....	23
3.4.3 Improvements in the photonic-crystal-cavity design	24
3.4.4 New developments in the analysis of experimental time traces	24
3.4.5 Brownian-Dynamics simulations	24
3.5 Integration on a single PCB	25
3.6 Status against the field-validation goal	26
3.7 Outlook beyond LEARN	27
4 Conclusions	28
4.1 VOC Sensor (INL).....	28
4.2 UFP Sensor (TU/e)	28

1 Introduction and Context

Deliverable D4.6 "Final Validation Report" is the closing deliverable of Work Package 4 (WP4: Novel Sensors UFPs & VOCs). Its objective is to consolidate, in a single public report, the final validation outcomes of the two LEARN novel sensors — the VOC sensor developed by INL and the UFP sensor developed by TU/e — and to assess each prototype against its design specifications, against reference measurement methods and, where applicable, against the indoor-air-quality conditions encountered during field deployment.

This deliverable follows directly on D4.5 ("Sensor Prototype (in the field) (v2)"), which described the engineering enhancements, school deployment and initial photoionisation acquisition for the VOC prototype, and the three-stage architecture and proof-of-principle detection chain for the UFP prototype. D4.5 explicitly deferred the comparative validation of the VOC measurements (against GC-FID analyses by KU Leuven) and the documentation of the complete UFP validation outcomes to the present deliverable.

Section 2 of this report is reserved for the INL contribution and presents the final validation of the VOC sensor in the school environment, including its comparison with the gold-standard reference method. Section 3 presents the TU/e contribution and gives the final validation status of the UFP sensor: the three-stage detection chain, the quantitative single-particle measurements, the integration progress, and the outlook for completion of the prototype after the LEARN project end. Section 4 provides the joint conclusions.

2 INL Volatile Organic Compound (VOC) Sensor

2.1 Introduction | Field Validation VOCs

The INL WP4 team has successfully designed, fabricated, and integrated multiple modules and validated a new prototype based on an innovative technology termed **Sample Ionisation Potential Spectroscopy (SIPS)**. This technology enables real-time molecular identification of Volatile Organic Compounds (VOCs). These achievements have been thoroughly documented in previous project deliverables and further disseminated through patent applications and scientific publications.

This deliverable reports the final outcomes of **Task 4.4 | Sensor Testing and Validation**, focusing on the evaluation of the VOC prototype in a real school environment. During this campaign, the performance of the VOC prototype was assessed under real operating conditions. The results obtained were validated through active air sampling, with the collected volatile organic compounds analysed using reference instrumentation, namely Gas Chromatography coupled with Flame Ionisation Detection (GC-FID). This comparative analysis confirms the reliability and robustness of the prototype for VOC monitoring in indoor environments.



Figure 1 Partial view of the room showing the VOC prototype

2.2 Experimental Methods | Field Validation

This section outlines the materials and methods employed during the field validation campaign of the VOC prototype. It details the procedures adopted for signal acquisition from the VOC prototype, the active air sampling strategy used for reference analysis, and the monitoring of relevant physical parameters. Together, these methodologies establish the experimental framework used to assess the prototype's performance under real-world conditions.

2.2.1 Photoionization signal acquisition

Taking in account D4.1, the VOCs validated in laboratory (BTEX group, reported in this manuscript <https://doi.org/10.1016/j.eti.2026.104895>) and the engineering features of the VOC prototype, the INL WP4 team selected for detection at the field eight VOCs: benzene, toluene, ethylbenzene and orto and para-xylene, styrene, limonene and naphthalene. Limonene was included because is a widely used chemical in cleaning and other daily products, and a VOC detected in WP3 Belgium cohorts.

2.2.1.1 VOC prototype signal acquisition

Data acquisition. The design of the routine for photoionization signal acquisition enables the attribution of currents detected to a photoionization process. Since we are dealing with volumetric gas, flux stabilization periods are incorporated in the protocol. Signal detection occurred at normal temperature and pressure (NTP) and applying a bias voltage of 50 V to create a driving electric field for an enhanced collection of the generated photoionization current.

A one-day measurement routine consisted of a timed loop collecting two data points per second:

1. A stabilization period of 360 s with the air collection pump already switched on.
2. Single VOC measurement: the VUV laser wavelength was automatically alternated twice between a pump wavelength respectively above ($\lambda_{\text{VUV-H}}$) and below ($\lambda_{\text{VUV-L}}$) the wavelength derived from the ionisation potential (λ_{IP}) of a given compound while the air matrix flowing into the ionisation chamber. Each measurement took 60s. The measurements were done sequentially from the lowest ionization potential (naphthalene 8.144 eV) to the highest ionization potential (benzene 9.24 eV).
3. A loop consisting of 8 VOC measurements, i.e. corresponding to 16 wavelength settings, was iterated 22x. A waiting period of 120 s was applied between loops.
4. A waiting period of 360s like step 1).

This day routine was performed over a period of fifteen days in a school environment, between February and March 2026. In total, for the field validation prototype using this routine the VOC prototype acquired more than 360 000 data points.

Figure 2 shows the LABVIEW front panel for the acquisition of 22 loops during the day for the field test validation.

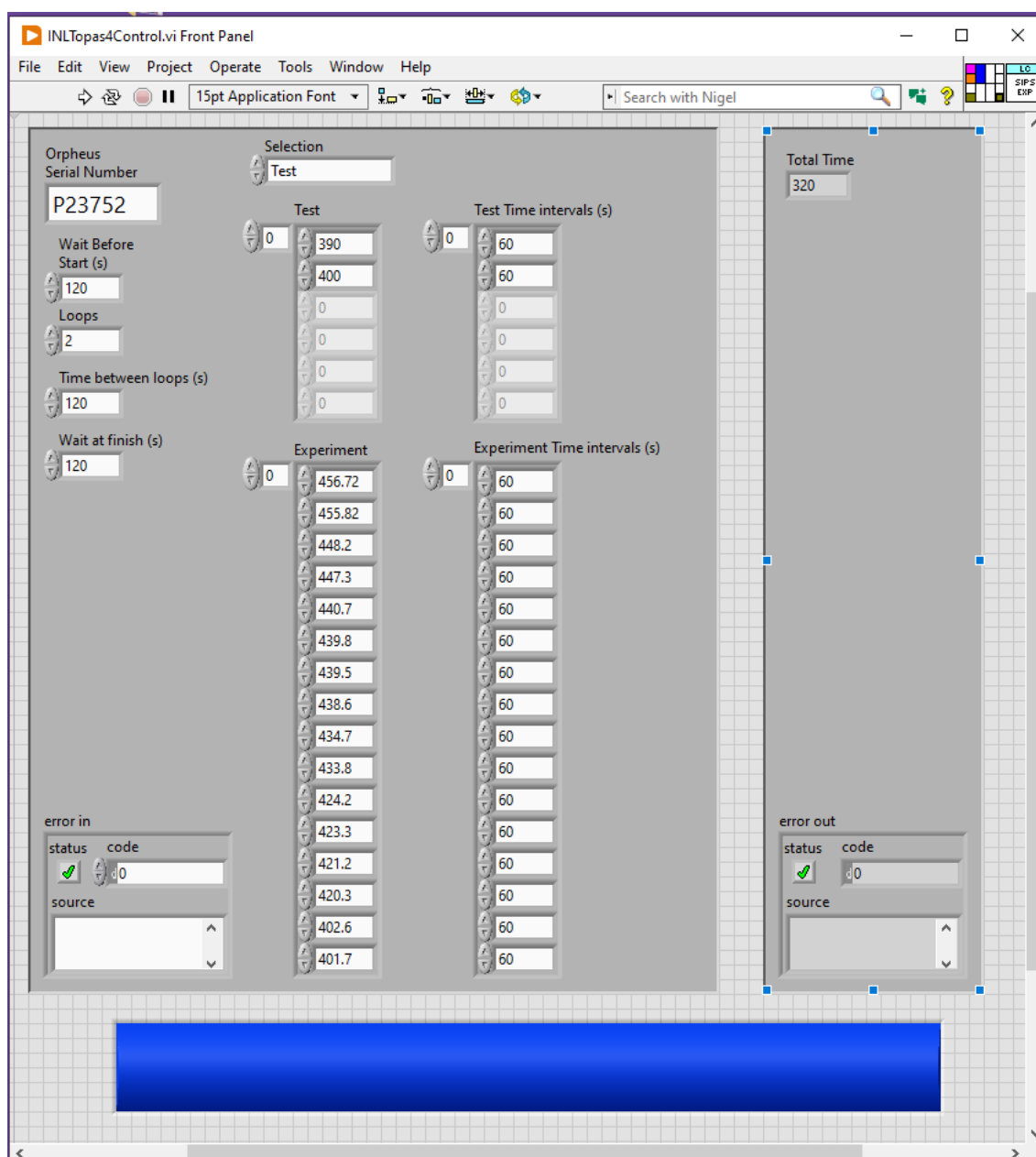


Figure 2 LabVIEW front panel implementing one-day routine acquisition.

Data processing. Data acquired with the VOC prototype was processed on MATLAB (version R2018b) on a code written by INL WP4 team. All heatmaps use a fixed, symmetric colour scale defined by the 98th percentile of the absolute signal across all datasets.

2.2.1.2 Active Sampling Methodology

To enable comparison with the results obtained from the VOC prototype, simultaneous active air sampling was conducted using activated carbon sorbent tubes.

Data acquisition. The flow rate chosen was the same as the VOC prototype: 200 mL/min and calibrated with a TSI 4146 device before each measurement. Air

collection was done by a Gilair Plus (Gilian) in low flow module to Charcoal Sorbent Tube (Sensidyne/Gilian) at near the inlet of the VOC prototype. The samples were collected at the same time of the VOC prototype acquisition, and fifteen samples were acquired in these conditions. For further understanding the origin of the VOCs, we collected additional samples outdoors at the entrance of the school. All the samples were stored at -20 °C before analysis and sent to process by the KU Leuven partner.

Data processing. Samples were characterized with gold standard analytical technique Gas Chromatography with Flame Ionisation Detection (GC-FID).

2.2.1.3 Environmental Parameters Monitoring

For a comprehensive knowledge of the environment where the VOC prototype was installed, we also monitored CO₂ level, temperature and humidity.

Data acquisition. CO₂ level, temperature and humidity were collected on a 24h basis with a SwitchBot Meter Pro (CO₂ Monitor). The monitor was placed on the top of the VOC prototype.

2.3 Results | Field Validation

This section presents the results obtained from the photoionization-based measurements performed during the field validation campaign of the VOC prototype in a school environment. The analysis focuses on the response of the prototype under real operating conditions, the outcomes of the reference active sampling, and the comparison between both datasets.

2.3.1 VOC Prototype Signal Response

During the deployment period, the VOC prototype acquired the photoionization signal in the school room from 9h to 18h. For each VOC, the VUV laser wavelength was automatically alternated twice between a pump wavelength respectively above ($\lambda_{\text{VUV-H}}$) and below ($\lambda_{\text{VUV-L}}$) the wavelength derived from the ionisation potential (λ_{IP}) of a given compound while the air matrix flowing into the ionisation chamber, as shown in table below.

Table 1 Ionisation Potentials, pump wavelengths

VOC	$E_{\text{IP}}(\text{eV})^{(29)}$	$\lambda_{\text{IP}}(\text{nm})$	$\lambda_{\text{VUV-H}}(\text{nm})$	$\lambda_{\text{VUV-L}}(\text{nm})$
Benzene	9.24	134.2	401.7	402.6
Toluene	8.83	140.4	420.3	421.2
Ethylbenzene	8.77	141.4	423.3	424.2
o-Xylene	8.56	144.9	433.8	434.7
Styrene	8.464	146.4	438.6	439.5
p-Xylene	8.44	146.9	439.8	440.7
Limonene	8.3	149.4	447.3	448.2
Naphthalene	8.144	152.2	455.8	456.7

Figure 3 shows representative maps of the voltage variation for the eight VOCs studied from 9h to 18h for three consecutive Fridays. Similar maps, not shown, were recorded for the other days.

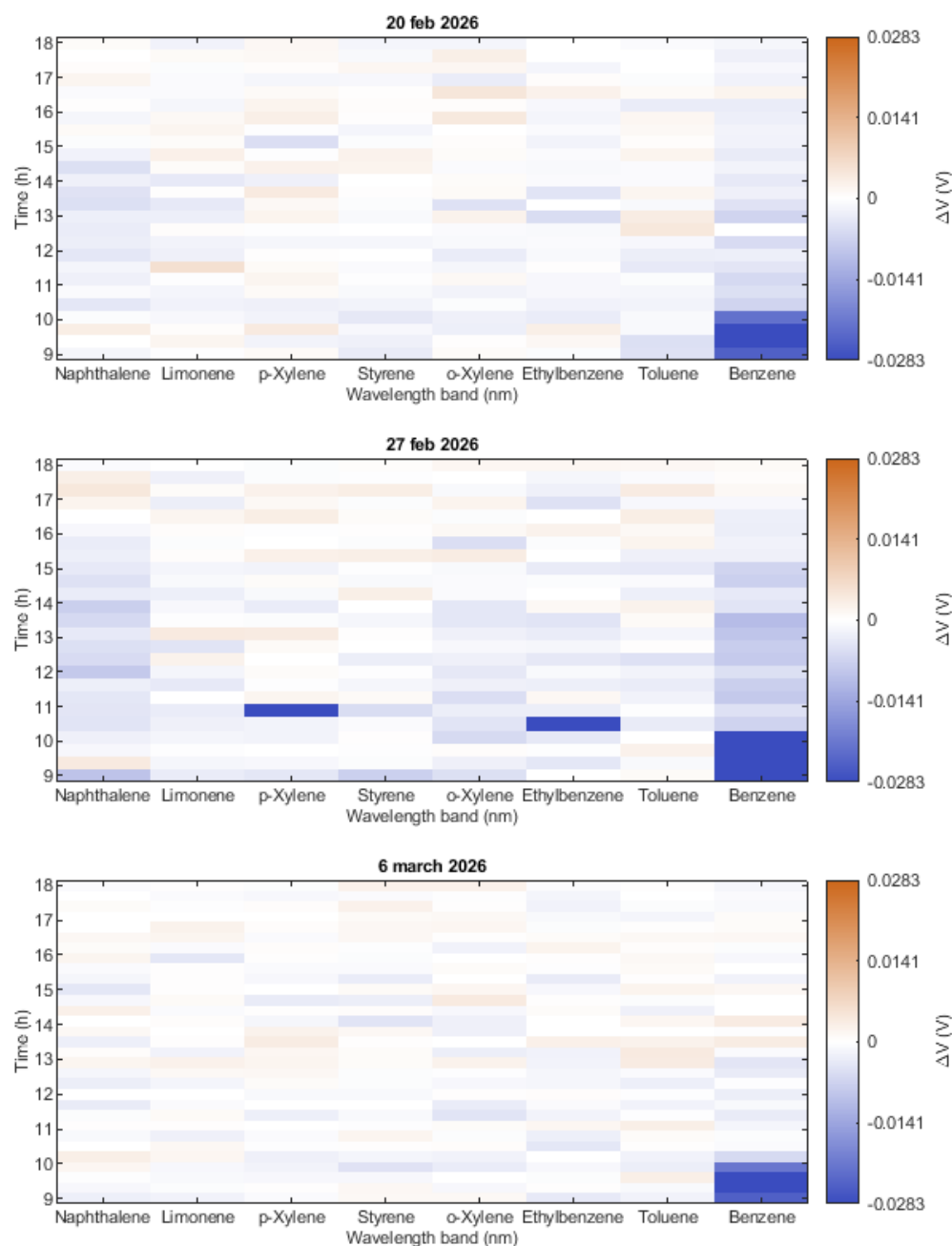


Figure 3 Representative map of temporal variation in signal intensity of the eight selected VOC's, acquired on the 20 February, 27 February and 6 of March 2026 (3 consecutive Fridays).

The recorded signals exhibited stable baseline behaviour over the monitoring period. Voltage variations corresponding to the characteristic ionisation wavelengths of the screened volatile organic compounds were consistently observed across multiple measurement days. Overall, the prototype demonstrated robust signal acquisition

capabilities during extended operation, confirming the suitability of the SIPS-based approach for real-time VOC screening.

2.3.2 Active Sampling and Reference Analysis Results

2.3.2.1 An Overview

Gas Chromatography – Flame Ionization Detection was used as reference instrumentation for the characterization of volatile organic compounds in the school environment. Table 2 shows the volume and time of the samples acquired in parallel with the VOC prototype (data sent to KU Leuven partner). Outdoors samples were also acquired to have a more comprehensive characterization of the origin of the VOCs in the school room.

Table 2 Parameters of the active sampling acquisition

#	Volume (L)	Time (min)
1	77.600	388
2	83.600	418
3	83.000	415
4	84.800	424
5	82.256	414
6	95.673	483
7	85.000	428
8	78.690	417
9	88.808	448
10	98.444	497
11	115.922	584
12	93.805	473
13	95.563	482
14	96.548	487
15	95.940	484

Apart from the BTEX compounds that will be analysed in detail, the results from GC-MS show the presence of alkanes, cycloalkanes, aromatic hydrocarbons and terpenes. Table 3 below shows the comprehensive list of VOCs identified along with the typical sources. Important to mention is that all VOCs are well below (ppb range) the Threshold Limit Value publish by the American Conference of Governmental Industrial Hygienists (ACGIH) set for 2024 as well as the Belgian limit values set by the Royal Decree of 16 Nov 2023.

Table 3 VOC Summary identified with the reference method indoors

Type	Compound	Typical Sources
Alkanes	2-Methylbutane	Fuel components, petroleum refining
	2-Methylpentane	Gasoline constituents

	3-Methylpentane	Fuel-related hydrocarbons
	n-Pentane	Fuel evaporation, petrochemical processes
	n-Hexane	Solvents, fuels, extraction processes
	n-Nonane	Diesel / fuel fractions
	n-Decane	Heavier fuel fractions, lubricants
Cycloalkanes	Cyclopentane	Petrochemical streams, foam blowing agents
	Cyclohexane	Solvent, chemical manufacturing
	Methylcyclopentane	Gasoline component, fuel-related
	Methylcyclohexane	Fuel blending, solvent uses
Aromatic hydrocarbons	Benzene	Fuels, petrochemicals (regulated / toxic)
	Toluene	Solvents, fuels, coatings
	Ethylbenzene	Fuel-related, styrene production
	o-Xylene	Fuels, paints, solvents
	m-Xylene	Solvents, petrochemical use
	3-Ethyltoluene	Refined fuels, petroleum derivatives
	1,2,3-Trimethylbenzene	Fuel blending, industrial solvents
	1,2,4-Trimethylbenzene	Fuels, coatings, industrial emissions
	Mesitylene (1,3,5-Trimethylbenzene)	Fuel additives, chemical synthesis
Terpenes	Limonene	Fragrances, cleaning products, biogenic sources

The analysis also retrieved unidentified compounds.

Table 4 shows the comprehensive list of VOCs identified along with the typical sources in the outdoors of the school. Despite being in the outdoors, near the city centre and important traffic routes all the VOC's identified were well below (ppb range) the Threshold Limit Value publish by the American Conference of Governmental Industrial Hygienists (ACGIH) set for 2024 as well as the Belgian limit values set by the Royal Decree of 16 Nov 2023.

Table 4 VOC Summary identified with the reference method indoors

Type	Compound	Typical Sources
Alkanes	2-Methylbutane	Fuel components, petroleum refining
	2,3-Dimethylbutane	Gasoline blending components
	2-Methylpentane	Gasoline constituents
	3-Methylpentane	Fuel-related hydrocarbons

	n-Hexane	Solvents, fuels, extraction and degreasing processes
Cycloalkanes	Methylcyclopentane	Gasoline component, fuel-related emissions
Aromatic hydrocarbons	Benzene	Fuels, petrochemical processes (toxic / regulated)
	Toluene	Solvents, fuels, coatings
	Ethylbenzene	Fuel-related, styrene production
	3-Ethyltoluene	Refined fuels, petroleum derivatives
	1,2,4-Trimethylbenzene	Fuels, coatings, industrial emissions

Comparing the results outdoors and indoors with the 8 VOCs in analysis, benzene, toluene, ethylbenzene, o-xylene and limonene were identified indoors, while outdoors only benzene, toluene and ethylbenzene were detected. In the next section we will be analysed further in depth the results obtained for the BTEX group both with the prototype and reference instrumentation.

2.3.2.2 Comparison Between VOC Prototype and Reference Measurements

There is a subset of 5 VOCs we pay particular attention to: benzene, toluene, ethylbenzene and xylene isomers (BTEX). These are the VOCs we utilized in the laboratory validation of the VOC prototype which is thoroughly described in a published manuscript. "Real-time molecular specific BTEX detection at TLV-TWA concentration levels" (<https://doi.org/10.1016/j.eti.2026.104895>). In this manuscript, we demonstrate for the first time the molecular specific and real-time detection of a calibrated mixture of BTEX VOCs. The limits of detection (LOD) of the VOC prototype were established for benzene, toluene, ethylbenzene, ortho and para xylenes. Therefore, we selected the results obtained with the BTEX group with the reference instrumentation to compare with the VOC prototype.

References measurements for BTEX group

Table 5 shows the results obtained for the BTEX group with the reference instrumentation (GC-FID) in section 1 (front section – primary adsorption zone) and in section 2 (back section – breakthrough indicator) of sorbent tubes. The results indicate that BTEX compounds were primarily retained in the front sorbent section, confirming valid concentration measurements.

From the xylene isomers only o-xylene was detected in two samples collected indoors. Consistent detection of toluene in the back section demonstrates partial sorbent breakthrough under high loading conditions, particularly at samples taken outdoors (OG1 and OG2), while benzene and higher aromatics remained fully retained. This suggests elevated toluene concentrations relative to sorbent capacity but no complete breakthrough. Overall, concentrations remained below applicable occupational exposure guidelines.

Table 5 BTEX concentration determined using the reference instrumentation using active sampling.

#	Section 1 – primary adsorption zone (µg/m ³)			Section 2 - breakthrough indicator (µg/m ³)						
	Benzene	Toluene	Ethylbenzene	o-Xylene	p-Xylene	Benzene	Toluene	Ethyl- benzene	o-Xylene	p-Xylene
1	4.7	14.6	4.4	0	0	0	6.7	0	0	0
2	4.5	13.4	0	0	0	0	6.6	0	0	0
3	4.1	11.8	3.6	0	0	0	6.7	0	0	0
4	4.3	11.9	0	0	0	0	6.8	0	0	0
5	5	14.7	4.1	0	0	0	6.7	0	0	0
6	4.1	13.5	0	3.2	0	0	5.4	0	0	0
7	5	19.9	4.4	0	0	0	7.9	0	0	0
8	4.9	11.2	0	0	0	0	5.4	0	0	0
9	4.4	13.1	0	3.7	0	0	5.4	0	0	0
10	3.9	9	0	0	0	0	10	0	0	0
11	3.3	8.9	3.2	0	0	0	4.5	0	0	0
12	3.9	11.1	0	0	0	0	6.8	0	0	0
13	4.2	10.7	0	0	0	0	4.3	0	0	0
14	3.7	11.6	3.2	0	0	0	6.1	0	0	0
15	4	10.7	3.8	0	0	0	6.6	0	0	0
OG1	14.9	38.8	12.9	0	0	0	21.9	0	0	0
OG2	13.5	34.8	0	0	0	0	27.9	0	0	0

The results obtained in section 1- primary adoption zone shown in the previous table were converted to ppb, assuming an ideal gas. Given p-xylene was not detected we excluded it from Table 6. Comparing the results obtained with the reference instrumentation with the VOC prototype it is evident that all the VOCs detected are below the LOD of the VOC prototype established in the laboratory environment.

Table 6 Comparison between the LOD determined for the BTEX group for laboratory validation with the VOC concentrations determined by GC-FID

	Benzene	Toluene	Ethylbenzene	o-Xylene
	Limit of Detection (LOD) (ppb) of the VOC prototype per laboratory validation			
	260	12220	5130	12230
#	Section 1 – primary adsorption zone (ppb) determined by reference instrumentation			
S1	1.471	3.874	1.013	0.000
S2	1.409	3.556	0.000	0.000
S3	1.283	3.131	0.829	0.000
S4	1.346	3.158	0.000	0.000
S5	1.565	3.901	0.944	0.000
S6	1.283	3.582	0.000	0.737
S7	1.565	5.281	1.013	0.000
S8	1.534	2.972	0.000	0.000
S9	1.377	3.476	0.000	0.852
S10	1.221	2.388	0.000	0.000
S11	1.033	2.362	0.737	0.000
S12	1.221	2.945	0.000	0.000
S13	1.315	2.839	0.000	0.000
S14	1.158	3.078	0.737	0.000
S15	1.252	2.839	0.875	0.000
OG1	4.664	10.296	2.971	0.000
OG2	4.226	9.324	0.000	0.000

Consistency between prototype screening results and reference instrumentation

Now, comparing these results with the maps of temporal variation in signal intensity for the BTEX group (3 representative maps are shown in Figure 3), the results obtained show that the variation of the voltage signal ranges from +/- 0.0283V for the 15 samples between 9 and 18h. From the laboratory validation (<https://doi.org/10.1016/j.eti.2026.104895>) we have established the VOC prototype sensitivity for each of the VOCs of the BTEX group and we also know that the VOC concentration is defined by

$$C_{BTEX} = \frac{\Delta I_{BTEX}}{S_{BTEX}}$$

and can be determined a timeframe of ~ 1 s and is principally dependent on the integration time of the integrating transimpedance amplifier and time required to shift the wavelength emission of the OPA.

Taking this in consideration, the ΔI_{BTEX} observed in the heatmaps are below the LOD of the BTEX compounds. Therefore, the signal variations observed constitute only instrumental noise variation across the 15 samples during 9h to 18h. The results obtained show that the prototype didn't record photoionization signals of the BTEX compounds analysed which is in accordance with the results obtained with the reference instrumentation. We have not recorded a false positive.

2.4 Conclusions

Within the framework of Task 4.4, the VOC prototype was successfully deployed and validated in a real school environment in Braga. The results obtained during the field campaign demonstrate the robustness and reliability of the prototype under real operating conditions.

3 TU/e Ultrafine Particle (UFP) Sensor

3.1 Overview and rationale

The objective of the TU/e contribution to WP4 is to develop a novel UFP sensor capable of detecting and counting individual ultrafine particles (diameter < 100 nm) in indoor air. Rather than relying on conventional condensation particle counters (CPCs) or optical particle counters (OPCs) — which are either too expensive, too bulky, or insufficiently sensitive for sub-100 nm particles — TU/e has pursued a fundamentally different approach based on fiber-tip photonic crystal cavities (PhCCs). The key insight underlying this approach is that nanoparticles in close proximity to a photonic-crystal cavity cause a measurable shift in the cavity's optical resonance wavelength; by monitoring this shift in real time, individual particles can be detected as they interact with the sensor.

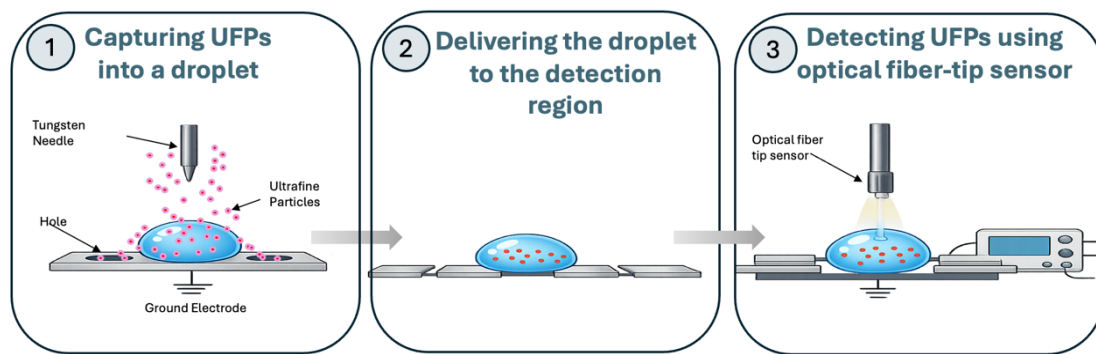


Figure 4: Schematic of three stage approach the detection of ultrafine particles from the air. (1): Capture of UFPs into liquid droplets (2): Transport of droplet to detection region (3): Detection of UFPs using fiber-tip PhCC sensor.

As established in D4.3 and D4.4, and reiterated in D4.5, the fiber-tip PhCC sensor operates most reliably in liquid rather than directly in air. To bridge the gap between airborne particles and liquid-phase detection, the TU/e team adopted a three-stage architecture (shown schematically in Figure 4), all to be integrated on a single printed-circuit board (PCB):

- **Stage 1** — Capture of UFPs into a liquid medium. The baseline route is inertial impaction of airborne particles onto the surface of a small water droplet, augmented by electrostatic delivery to recover the capture efficiency that inertial forces alone cannot deliver in the sub-100 nm range. As a complementary route, we also explore capture of UFPs directly onto a solid surface (PCB / electrode), with subsequent transfer of the captured particles into a droplet that is moved over the collection area.
- **Stage 2** — Transport of the particle-laden droplet on the same PCB substrate. The baseline route is electrowetting-on-dielectric (EWOD); we additionally explore a dielectrophoretic (DEP) actuation variant that enables open-design droplet generation in the impactor zone and droplet agitation, both of which are needed to support Stage 1.
- **Stage 3** — Detection of single UFPs in the droplet via the fiber-tip PhCC sensor at a fixed location on the PCB.

Compared with D4.5, the present deliverable extends each of the three stages with new results obtained in the closing months of the project. Stage 1 is reinforced by simulations of electrostatic precipitation that quantify the gain over inertial-only

capture for sub-100 nm particles, by a generation of CAD-designed and 3D-printed impactor prototypes, and by the introduction of the alternative solid-surface capture route. Stage 2 is extended with the practical implementation of EWOD on PCB and with a DEP actuation variant that addresses the limitations of EWOD in an open geometry. Stage 3 is extended with concentration-series measurements that systematically link wavelength-shift statistics to particle concentration, with improvements in the photonic-crystal-cavity design, with new analysis developments, and with Brownian-Dynamics (BD) simulations that allow a semi-quantitative comparison with the experimental data. The present section reports the consolidated final validation outcomes for each stage, the status of integration on a single PCB, and the path toward a fully operational UFP sensor prototype beyond the LEARN project end.

3.2 Stage 1 — Capture of UFPs

Stage 1 has the task of moving airborne ultrafine particles into a state in which they can be detected by the fiber-tip PhCC sensor of Stage 3. As established in D4.5, the baseline route is to capture the particles directly into a small liquid droplet held at a defined position on the PCB. Two capture mechanisms in the droplet route have been characterised: inertial impaction, which was the route demonstrated end-to-end in the proof-of-principle chain reported in D4.5, and electrostatic delivery, which is the high-efficiency mechanism required for the sub-100 nm range. In addition, a complementary route is now also being explored: capture of UFPs directly onto a solid surface (the PCB / electrode), followed by transfer of the captured particles into a droplet that is moved over the collection area in Stage 2. The three options are described in turn.

3.2.1 Inertial impaction into a droplet

In the inertial-impaction configuration, an air sampling inlet draws ambient air through a defined flow path that directs the particles toward the surface of a liquid droplet held at a fixed position above a PCB-based impactor plate with through-hole air outlets. Particles cross the droplet streamlines and are captured by impaction (large particles) and diffusion (small particles). This is the configuration that underpins the proof-of-principle detection chain reported in D4.5, in which UFPs were captured in a droplet, the droplet manually transferred to the fiber-tip detector, and individual particles detected.

Compared with D4.5, the impactor hardware has matured into a family of CAD-designed, 3D-printed prototypes with controlled inlet/outlet geometries that can be matched to the impactor plate on the PCB and to the droplet position. These prototypes are used as the experimental platform for the inertial-capture characterization and as the geometrical reference for the electrostatic-precipitation simulations described in section 3.2.2.

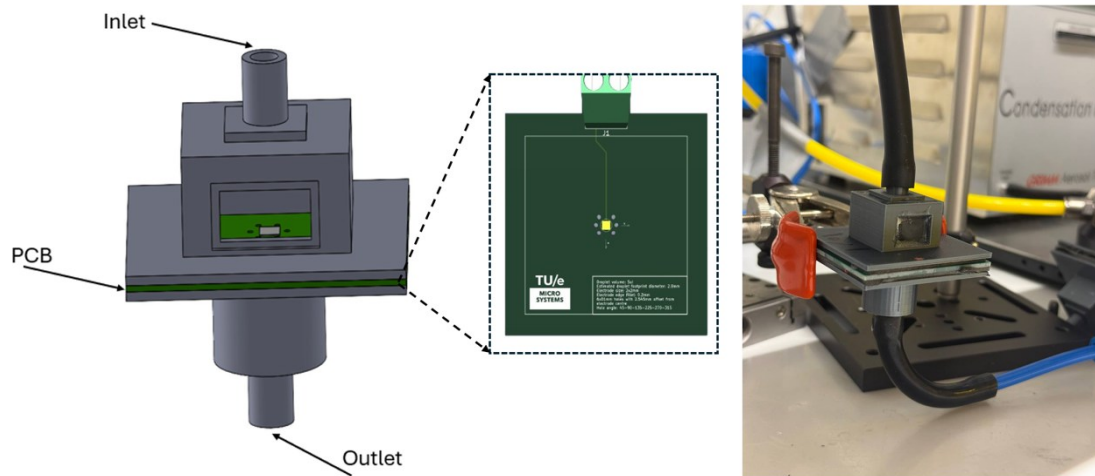


Figure 5: Left: CAD visualization of an impactor test design with integrated PCB. Right: Photograph of the test impactor being used in experiments in the lab.

As already noted in D4.5, ultrafine particles have very low inertia and tend to follow the air streamlines rather than impacting the droplet surface. As a consequence, inertial capture alone provides only a modest capture efficiency in the sub-100 nm range and requires prolonged droplet exposure times to reach detectable particle populations for typical indoor concentrations ($\approx 10^3\text{--}10^4\text{ cm}^{-3}$). This finding directly motivates the electrostatic-augmented capture route described next.

3.2.2 Electrostatic delivery — simulation

In the electrostatic-delivery configuration, particles are first electrically charged in a unipolar charger and then driven into the droplet by an applied electric field, dramatically increasing capture efficiency, in particular below 100 nm. The implementation of this stage in the laboratory required a high-voltage setup that, as reported in D4.5, was delayed by institutional safety-compliance procedures for high-voltage equipment. To characterise and de-risk this configuration in parallel with the experimental commissioning, TU/e has carried out a campaign of finite-element simulations covering both the corona discharge in the unipolar charger and the trajectories of the charged particles inside the impactor.

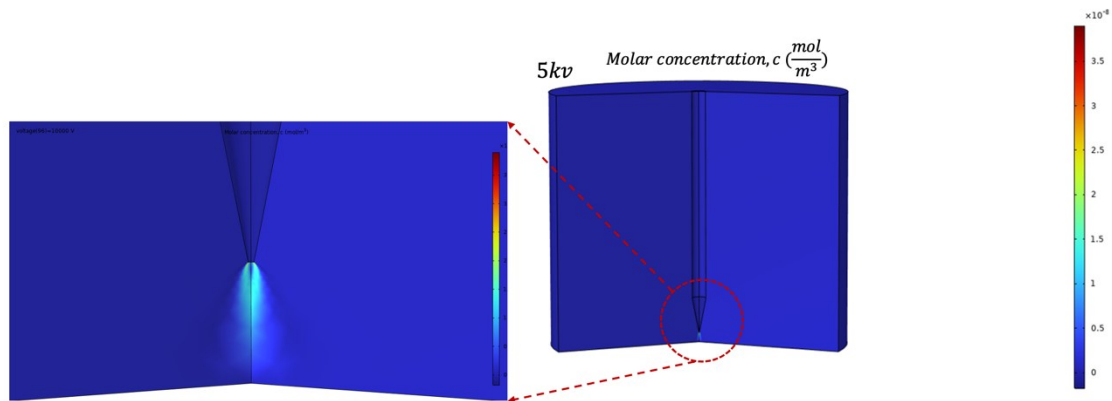


Figure 6: Finite-element simulation of the corona discharge in the unipolar charger that precedes the impactor (2D axisymmetric, needle at 10 kV). Left: ion molar concentration in the (r, z) plane, showing the unipolar-ion plume from the needle tip toward the ground electrode. Right: 3D revolution of the geometry.

Figure 6 shows a representative result of the corona-discharge simulation. The model is implemented as a 2D axisymmetric finite-element problem in which a $100\text{ }\mu\text{m}$ -tip, 50 mm-long needle electrode faces a 4 mm-diameter grounded counter-electrode across a 20 mm gap. At an applied needle voltage of 10 kV, a localised high-field region forms at the needle tip, and a stable corona develops along the symmetry axis, producing a plume of unipolar ions that drifts toward the ground electrode under the applied field. The simulated ion molar concentration peaks at a few $\times 10^{-8}\text{ mol m}^{-3}$ near the needle tip and decays as the plume spreads downstream, providing the quantitative basis for sizing the corresponding laboratory charger to deliver the ion flux required to charge the UFP aerosol prior to impaction.

Coupled to this charger model, a second set of simulations follows the trajectories of the charged particles inside the impactor itself and predicts the capture efficiency on the droplet as a function of particle size for the inertial-only and the electrostatic-augmented configurations. The result confirms — and quantifies — the qualitative argument made in D4.5: in the sub-100 nm range, electrostatic delivery increases the capture efficiency by a large factor relative to inertial impaction alone, while leaving the larger-particle behaviour of the impactor essentially unchanged.

3.2.3 Alternative — UFP capture on a solid surface

In parallel to the droplet-capture route, a complementary capture strategy is being developed in which the UFPs are first deposited directly onto a solid surface — typically the PCB itself, or the surface of an EWOD/DEP electrode — and only afterwards transferred into a droplet. In this scheme, after a defined collection time, a droplet is moved over the PCB region on which the UFPs have accumulated and the particles are transferred into the liquid in transit, where they then become accessible to the fiber-tip detector.

This solid-surface capture route has two attractive properties. First, it removes the requirement that a droplet be present at the impactor location during the air-sampling phase, which simplifies the impactor design and decouples the air-sampling and droplet-handling cycles in time. Second, it integrates naturally with Stage 2: the very same droplet that is used for transport to the detection zone is also the agent that picks up the particles from the surface, provided that the droplet motion or shape oscillation can be controlled actively (see section 3.3.3 on the dielectrophoresis variant of electrowetting).

3.3 Stage 2 — Droplet handling on the PCB

Stage 2 is responsible for handling the droplet on the PCB: bringing it to the impactor location for capture, transporting it across the board to the fiber-tip detector, and — where applicable — agitating it on a collection area to transfer surface-deposited particles into the liquid (the alternative route introduced in section 3.2.3). The baseline actuation mechanism is electrowetting-on-dielectric (EWOD), demonstrated on glass already in D4.5 and now extended to PCB. To address the limitations of EWOD in an open geometry, we additionally develop a dielectrophoretic (DEP) actuation variant.

3.3.1 EWOD on glass — reference validation

EWOD actuation has been validated on glass-based reference devices, on which the dielectric and hydrophobic coating quality can be tightly controlled. Reliable droplet motion has been demonstrated across electrode arrays of the geometry used in the integrated prototype, at actuation voltages within the range targeted for the on-board high-voltage driver. As reported in D4.5, these reference experiments confirmed the viability of the EWOD-based transport scheme and provided the baseline against which the on-PCB performance is now compared.

3.3.2 Practical implementation of EWOD on PCB

As anticipated in D4.5, the principal challenges in transferring EWOD from glass to PCB are (i) the local steps and surface roughness introduced by the copper electrodes (typically several hundred micrometres thick on a standard PCB), and (ii) the difficulty of achieving sufficient and uniform hydrophobicity on the PCB surface — even after coating with SU-8 photoresist and Aquapel. The mitigation strategies pursued in parallel — alternative PCB suppliers with tighter surface tolerances, planarisation procedures to fill the gaps around the electrodes, and alternative dielectric/hydrophobic coatings — were already outlined in D4.5.

Building on this, the present deliverable reports the practical implementation of EWOD on a series of PCB prototypes that have been designed, fabricated and tested in the closing months of the project. Selected outcomes of these tests, and the dielectrophoretic variant explored on the same platform, are presented together in section 3.3.3 below.

3.3.3 Dielectrophoretic (DEP) actuation as a complementary variant

Beyond classical EWOD, TU/e has investigated a dielectrophoretic actuation variant of electrowetting on the same PCB platform. In this configuration, the droplet is manipulated by the gradient of the applied electric field rather than by the local change of contact angle on a dielectric-covered electrode. This DEP variant has two properties that are particularly relevant to the LEARN UFP sensor:

- Open-design droplet generation. Conventional EWOD requires a closed device geometry — a top plate forming the second wall of a thin liquid layer — to dispense a droplet from a reservoir. The impactor zone of the LEARN UFP sensor must, however, remain open to the air flow, which makes a closed EWOD geometry impractical at that location. The DEP variant supports droplet dispensing from a reservoir on an open device, and is therefore a natural fit to the open-impactor architecture: a droplet can be formed on demand, brought to the impactor, exposed to the air flow, and subsequently transported to the detection zone.

- Active droplet agitation. The DEP actuation can be operated in a mode in which the droplet is repeatedly spread to a thin, flat shape on the electrode array and then allowed to recoil into a more spherical shape. This shape oscillation continuously refreshes the contact area between the droplet and the surface and is expected to facilitate the transfer of particles deposited on the surface into the bulk of the droplet — exactly what is required by the alternative solid-surface capture route introduced in section 3.2.3.

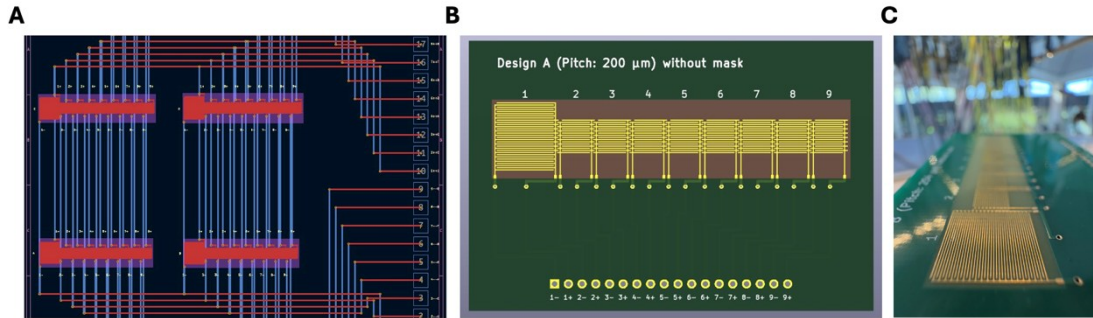


Figure 7: Fabrication of interdigitated electrodes on PCB. (A) CAD design of test PCB device with interdigitated electrodes (B) Zoom-in on one device with reservoir at the left and a train of electrode patches for transporting droplets. (C) Photograph of finished PCB device.

A first PCB test platform for these DEP experiments has been designed and fabricated (Figure 7). The board carries several interdigitated-electrode test devices (panel A), each combining a reservoir on the left with a train of nine electrode patches for droplet transport (panel B; design A, 200 μm pitch, without dielectric mask). Initial experiments on this board (panel C) are now underway.

3.4 Stage 3 — Single-particle detection by the fiber-tip PhCC sensor

Stage 3 is the most mature stage of the TU/e UFP sensor and the one in which the most extensive final validation has been performed. Compared with D4.5, the present deliverable extends the Stage-3 validation in four directions: (i) systematic concentration-series measurements that link the wavelength-shift statistics to the particle concentration in the droplet; (ii) improvements in the photonic-crystal-cavity (PhCC) design; (iii) new developments in the analysis of the experimental time traces; and (iv) Brownian-Dynamics (BD) simulations that allow a semi-quantitative comparison with the experimental data.

3.4.1 Sensor architecture and read-out

The sensor consists of a photonic-crystal nanostructure fabricated on the cleaved tip of a single-mode optical fiber. When a particle enters the evanescent field of the cavity, it perturbs the resonance condition and produces a measurable shift $\Delta\lambda$ in the resonant wavelength. The fiber is connected either to a wavelength interrogator (Hyperion SI255) that continuously sweeps over 1460–1620 nm, or to a tunable laser parked on the side of the PhCC resonance. In both cases, the analysis of the reflected signal yields a live time-trace of the resonant wavelength, in which sharp peaks correspond to individual particle-detection events. As reported in D4.4 and reiterated in D4.5, single-particle detection has been demonstrated for sizes from 500

nm down to 50 nm in nominal diameter at particle number concentrations in the $10^8 - 10^{11} \text{ cm}^{-3}$ range in ultra-pure water (UPW).

3.4.2 Concentration-series measurements

To validate the fiber-tip detector as a quantitative concentration sensor — and not only as a single-particle counter — measurements were performed on a series of monodisperse polystyrene-bead suspensions in ultra-pure water, in which both the particle number concentration and the particle size were systematically varied. For each (size, concentration) pair, the wavelength-shift time trace $\lambda_0 - \lambda(t)$ was recorded and the corresponding histogram $p(\Delta\lambda)$ of detected wavelength shifts was extracted. The expected behaviour for an ideal concentration sensor is that the event rate, integrated over $\Delta\lambda$, scales linearly with the particle number concentration. The particle contribution to $p(\Delta\lambda)$ has a shape that is set by the size distribution and the cavity geometry and is, to first order, independent of concentration; the measured histogram, however, is the sum of this particle contribution and a fixed baseline-noise contribution centered on $\Delta\lambda \approx 0$. As a result, the observed $p(\Delta\lambda)$ curves at different concentrations are not identical: at low concentrations they are dominated by the baseline-noise peak, while at higher concentrations the particle long-tail emerges progressively above this baseline.

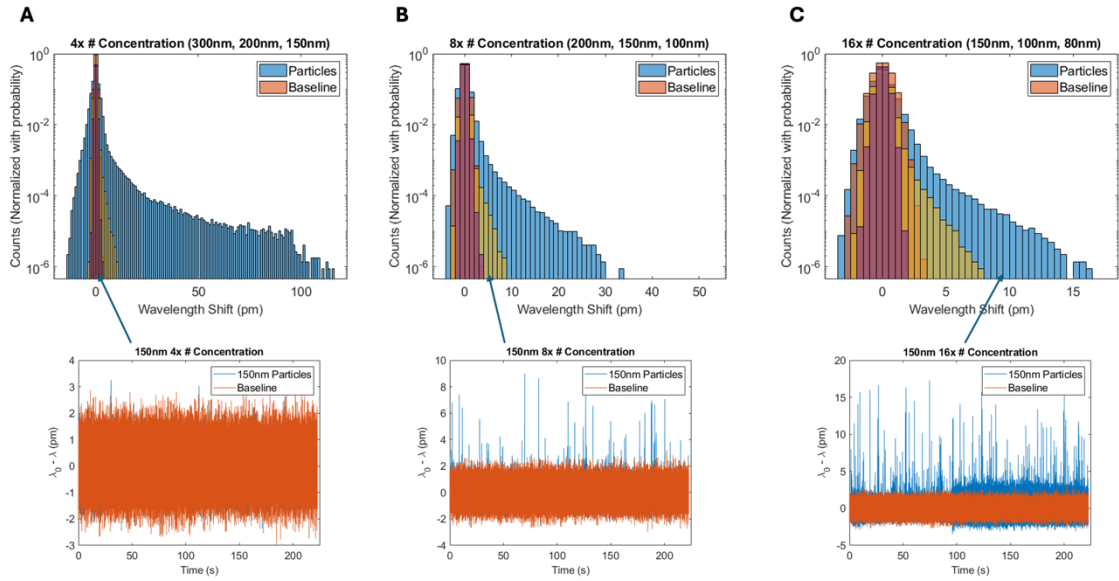


Figure 8: Wavelength-shift measurements with the fiber-tip PhCC sensor on monodisperse polystyrene-bead suspensions in ultra-pure water, at three number concentrations spaced by factors of two — A: 4×, B: 8×, C: 16× of a base concentration of 3.5×10^9 particles cm^{-3} (i.e. 1.4×10^{10} , 2.8×10^{10} , and 5.6×10^{10} particles cm^{-3}). Top: histograms $p(\Delta\lambda)$ for three particle sizes per panel (sizes given in the panel titles), with the baseline-noise distribution acquired in ultra-pure water; arrows mark the 150 nm histogram. Bottom: corresponding wavelength-shift time traces $\lambda_0 - \lambda(t)$ for the 150 nm particles, with the baseline trace overlaid.

These trends are illustrated by the representative dataset of Figure 8, which shows wavelength-shift time traces and histograms at three number concentrations spaced by factors of two: 4×, 8×, and 16× of a base concentration of 3.5×10^9 particles cm^{-3} — i.e. 1.4×10^{10} , 2.8×10^{10} , and 5.6×10^{10} particles cm^{-3} in columns A, B, C respectively. Each histogram overlays three particle sizes, chosen so that 150 nm is the common size across all three columns; the corresponding time trace $\lambda_0 - \lambda(t)$ for

the 150 nm particles is shown below each histogram, together with the baseline acquired in ultra-pure water. At 4× concentration (A) the 150 nm signal is essentially buried in the ± 3 pm baseline noise, and its histogram (arrow) overlaps the baseline peak; at 8× (B) discrete detection events of a few pm rise above a baseline of similar amplitude and the histogram develops a clear long-tail beyond 3 pm; at 16× (C) the detection peaks reach up to 17 pm and dominate the histogram out to about 15 pm. The same long-tail behaviour appears at fixed concentration when the particle size is increased — the histograms of the larger sizes within each column extend to progressively larger $\Delta\lambda$ — providing the size-dependent observable used by the multiparameter analysis pipeline of section 3.4.5.

3.4.3 Improvements in the photonic-crystal-cavity design

In parallel with the validation of the existing detectors, the PhCC design has been refined with the goal of improving the sensitivity of the resonance wavelength to the presence of nanoparticles in the evanescent field, and of making the detection events more easily distinguishable from the noise baseline.

3.4.4 New developments in the analysis of experimental time traces

As anticipated in D4.5, a major focus of the validation work is the conversion of the recorded time traces into a quantitative estimate of both the size distribution and the number concentration of the particles in the droplet. Three observables are used:

- the event rate, i.e. the number of detected peaks per unit time, which is dominated by concentration;
- the distribution of resonance-shift amplitudes $p(\Delta\lambda)$, which depends on both size and concentration;
- the temporal dynamics of the individual events, which encode the diffusion rate of the particles and therefore their size, via the characteristic dwell time of a particle in the evanescent field.

In the closing months of the LEARN project, this multiparameter analysis has been further developed in two directions: an improved peak-detection and event-classification pipeline that is more robust against baseline drift and laser noise, and a model-based estimator that fits the observed (event-rate, $p(\Delta\lambda)$, dwell-time) triplets against a library of simulated traces to extract size and concentration jointly.

3.4.5 Brownian-Dynamics simulations

To support the multiparameter analysis of the experimental data, we have developed Brownian-Dynamics (BD) simulations of the particle motion in the vicinity of the fiber tip. The simulations track individual diffusing particles in the geometry around the fiber tip and predict, for a given size and concentration, the expected event rate, the histogram of resonance-shift amplitudes, and the dwell-time distribution of the events. We simulate the trajectories of colloidal particles near a planar sensor surface using overdamped Brownian dynamics. Each particle is propagated under thermal Langevin forcing plus DLVO and steric wall interactions, with the bulk diffusion coefficient given by Stokes–Einstein and the integration timestep adapted per particle size to stay well within the overdamped regime. At every 10 ms snapshot the optical observable is computed as an evanescent-weighted volume integral over particles inside a $3.5 \times 3.5 \mu\text{m}$ sensor patch, with field decay length 200 nm. The example shown here sweeps five particle diameters (80–300 nm) against eleven number concentrations doubling from 10^7 to 10^{10} cm^{-3} , with

five replicate runs per parameter set of 240 s each, matching the duration of representative experimental recordings.

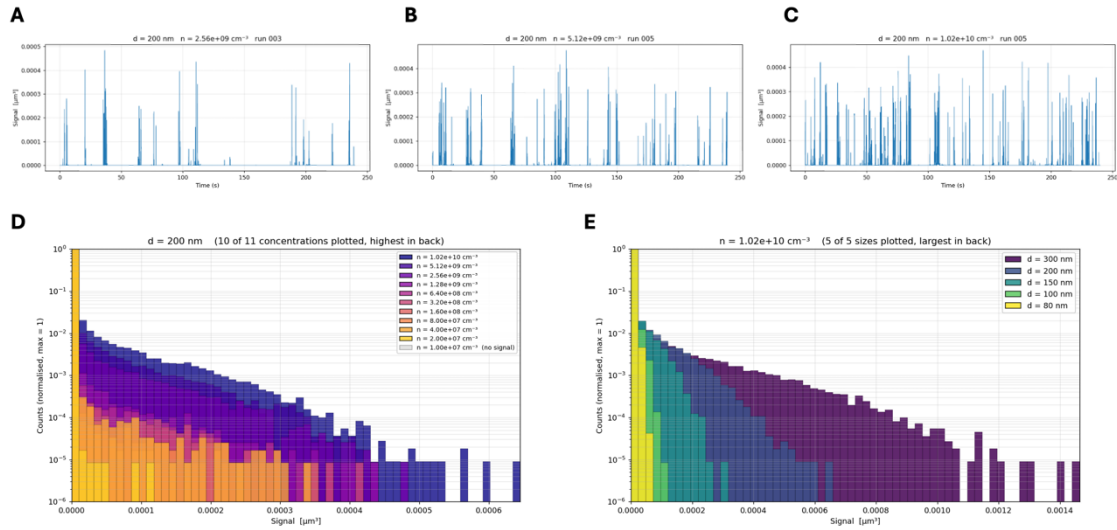


Figure 9: Brownian-Dynamics (BD) simulation of the fiber-tip PhCC response to monodisperse polystyrene particles in water. (A–C) Simulated time traces of the detection signal for $d = 200$ nm at three concentrations $n = 2.56 \times 10^9$, 5.12×10^9 , and $1.02 \times 10^{10} \text{ cm}^{-3}$. (D) Simulated signal histograms at $d = 200$ nm for concentrations spanning 1×10^7 – $1.02 \times 10^{10} \text{ cm}^{-3}$ (highest in back). (E) Simulated histograms at $n = 1.02 \times 10^{10} \text{ cm}^{-3}$ for five particle sizes (80, 100, 150, 200, 300 nm; largest in back). Histograms are normalised to their maximum count.

To support the interpretation of the experimental data and to underpin the multiparameter (size, concentration) estimator of section 3.4.4, Brownian-Dynamics (BD) simulations of the fiber-tip PhCC response were performed for monodisperse polystyrene particles in water, spanning approximately the same operating range as the laboratory experiments (Figure 9). At a fixed particle diameter $d = 200$ nm and increasing number concentration (panels A–C, $n = 2.56 \times 10^9$, 5.12×10^9 , and $1.02 \times 10^{10} \text{ cm}^{-3}$), the simulated rate of detection events grows monotonically with concentration, as expected for an ideal single-particle counter. The corresponding signal histograms, shown in panel D for concentrations spanning 1×10^7 – $1.02 \times 10^{10} \text{ cm}^{-3}$, exhibit a long signal-tail that emerges and grows progressively as the concentration is increased. At fixed concentration and varying particle size (panel E, $n = 1.02 \times 10^{10} \text{ cm}^{-3}$, $d = 80, 100, 150, 200$, and 300 nm), both the amplitude and the extent of the long-tail of the histogram grow with size. The two trends — concentration-driven amplitude of the tail, and size-driven amplitude-and-extent of the tail — provide the orthogonal observables on which the multiparameter (size, concentration) estimator of section 3.4.4 is built.

3.5 Integration on a single PCB

The target architecture for the UFP sensor integrates the three stages on a single PCB, on which the board acts simultaneously as the structural substrate, the EWOD/DEP electrode array, the impactor bottom plate (with through-hole air outlets) and/or the solid-surface UFP collection area, and the mounting platform for the fiber-tip sensor. At the level of the individual stages, all three building blocks have been validated as described in Sections 3.2 to 3.4. PCB prototypes have been fabricated and have been used to demonstrate EWOD-driven droplet motion on PCB substrates (section

3.3.2), to explore the DEP variant for open-design droplet generation and agitation (section 3.3.3), and to host the impactor / capture geometry of Stage 1 (section 3.2). The remaining integration milestones at the time of writing are: (i) demonstration of EWOD- or DEP-driven transport of a particle-laden droplet from the capture zone to the fiber-tip on a single PCB; (ii) demonstration of an end-to-end air-to-detection cycle on the integrated PCB, ideally using electrostatic-augmented capture or, alternatively, the solid-surface capture route of section 3.2.3 with droplet-based pick-up; and (iii) integration of the optimised PhCC fiber-tip sensor of section 3.4.3 in the on-PCB detection slot.

3.6 Status against the field-validation goal

As reported in D4.5, the UFP sensor prototype has not reached full field-deployment readiness within the LEARN project timeline. The reasons for this — late integration of TU/e into the consortium, the adoption of a fundamentally new fiber-tip-PhCC sensing concept that required substantial fundamental research, the high-voltage safety-compliance delay on the electrostatic-capture stage, and the surface-quality challenges in transferring EWOD from glass to PCB — were already documented in detail in D4.5 and are not repeated here. The consortium's response was the rescheduling of milestone MS8 from M44 to M47, formalised in the project amendment.

Within these constraints, the validation work reported in this deliverable establishes that:

- The fiber-tip PhCC detector reliably detects single particles down to 50 nm in diameter, the wavelength-shift event rate scales monotonically with particle concentration over the validation range (section 3.4.2), and the multiparameter analysis pipeline of section 3.4.4, supported by the BD simulations of section 3.4.5, provides a quantitative route to size and concentration estimation.
- The inertial-impaction capture stage has matured into a family of CAD-designed, 3D-printed impactor prototypes (section 3.2.1) and electrostatic-precipitation simulations on those geometries quantify the very large gain delivered by electrostatic-augmented capture in the sub-100 nm range (section 3.2.2).
- An alternative solid-surface capture route is being developed (section 3.2.3), in which UFPs are first deposited on the PCB and subsequently transferred into a droplet by surface contact and droplet agitation — a route that integrates naturally with the DEP actuation variant introduced in Stage 2.
- EWOD-based droplet transport, validated on glass in D4.5, has been implemented in practice on PCB and demonstrated in a series of test boards (section 3.3.2); a dielectrophoretic actuation variant has been added to enable open-design droplet generation in the impactor zone and droplet agitation for the solid-surface capture route (section 3.3.3).
- The proof-of-principle detection chain reported in D4.5 — capture, droplet transfer, fiber-tip detection — has been confirmed and quantitatively extended through the concentration-series measurements of section 3.4.2.

The remaining gap to a field-deployable prototype is therefore concentrated in (i) the PCB-level integration of the three stages on a single board and (ii) the closing of the electrostatic-capture and on-PCB EWOD/DEP chains. Both items are scoped within the ongoing TU/e PhD trajectories (Hasan Yalcinoglu, started Nov. 2023; Mostafa Taghipour, started Apr. 2024), each of which extends approximately two years beyond the LEARN project end.

3.7 Outlook beyond LEARN

Task 4.4 (Sensor Testing and Validation) remains active until the end of the LEARN project. The consolidation of the validation results reported in this deliverable, together with the integration milestones identified in Sections 3.5 and 3.6, defines the technical roadmap that the TU/e team will follow in the closing months of the project and in the immediate post-project period. Concretely, the focus of the remaining LEARN period is on closing the electrostatic-capture chain and reaching reproducible EWOD actuation on the integrated PCB.

Beyond LEARN, the two TU/e PhD students will continue to work on the UFP sensor for approximately two more years, ensuring that the fundamental research investment made within LEARN is carried to maturity. The expected post-project milestones include the full PCB-level integration of the three stages, an extended field-validation campaign against a commercial reference UFP counter, and the dissemination of the underlying methodology in the peer-reviewed literature.

It is important to note, as already underlined in D4.5, that the delay on the UFP prototype does not critically affect the other LEARN deliverables or milestones: no other work package critically depends on the TU/e UFP sensor for its activities, and the originally foreseen collaboration with WP6 (Task 6.3) has been adjusted so that Mann+Hummel uses a commercial UFP sensor for its validation tests.

4 Conclusions

This deliverable consolidates the final validation outcomes of the two LEARN novel sensor prototypes and assesses each against its design specifications and against reference measurement methods.

4.1 VOC Sensor (INL)

The INL VOC sensor — the SIPS (Sample Ionisation Potential Spectroscopy) prototype — was successfully field-validated in a real classroom environment in Braga, Portugal, over a 15-day campaign in February–March 2026 covering the eight target VOCs. Comparative analysis against GC-FID reference samples processed by KU Leuven showed classroom BTEX concentrations below both the prototype's limit of detection and the ACGIH 2024 / Belgian regulatory thresholds; consistently, the prototype recorded no false-positive photoionisation signals, confirming the robustness, selectivity and operational stability of the SIPS-based approach for real-time indoor VOC screening. The underlying methodology has been disseminated through peer-reviewed publications and patent applications, and INL will continue development of the prototype beyond LEARN.

4.2 UFP Sensor (TU/e)

The TU/e UFP sensor has progressed from the proof-of-concept single-particle detection of D4.3/D4.4 and the proof-of-principle detection chain of D4.5 to a quantitatively validated three-stage architecture: simulation- and impactor-supported particle capture (Stage 1), EWOD- and DEP-actuated droplet handling on PCB (Stage 2), and concentration-series-validated single-particle detection by the fiber-tip photonic-crystal-cavity sensor, supported by Brownian-Dynamics simulations and a refined cavity design (Stage 3). As already documented in D4.5, full field-deployment readiness has not been reached within the LEARN timeline; the remaining gap — PCB-level integration and the closing of the electrostatic-capture and on-PCB EWOD/DEP chains — is scoped within the two TU/e PhD trajectories that will continue beyond the project end.