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Open and FAIR data for nanofiltration in organic media: A unified approach

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A R T I C L E I N F O

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A B S T R A C T

Organic solvent nanofiltration (OSN), also called solvent-resistant nanofiltration (SRNF), has emerged as a promising technology for the removal of impurities, recovery of solutes, and the regeneration of solvents in various industries, such as the pharmaceutical and the (petro)chemical industries. Despite the widespread use of OSN/SRNF, the presence of scattered, non-standardized data, and the absence of openly accessible data pose critical challenges to the development of new membrane materials and processes, their comparison to the state-of-the-art materials, and their fundamental understanding. To overcome these hurdles, data from peer-reviewed research articles and commercial datasheets were curated via a standardized procedure to obtain an extensive dataset on the membrane materials, synthesis parameters, operational conditions, physicochemical properties, and performance of OSN/SRNF membranes. Thanks to a truly impressive joint effort of the OSN/SRNF community, the dataset contains, as per April 2024, 5006 unique membrane filtrations from 294 publications for 42 solvents under several process parameters. This findable, accessible, interoperable, reproducible, and open (FAIR/O) dataset is available on both the OSN Database and the newly inaugurated Open Membrane Database for SRNF (OMD4SRNF). These databases provide multiple visualization and data exploration tools. Here, the standardized procedure applied to curate the data and the functionality of the databases are outlined, as well as the online user interface to deposit new data by external users on the OMD4SRNF. This community-led project has been supported by all the co-authors of this work. Most importantly, they additionally agreed to systematically deposit their future peer-reviewed data on OSN/SRNF into the databases. We thereby pave the road for FAIR/O data in the field of OSN/SRNF to increase transparency, enable more accurate data analysis, and foster collaboration and innovation.

1. Introduction

The urgent societal and environmental challenges the world is facing require an equally urgent acceleration of solutions provided by, amongst others, research and technology. It is crucial to tackle the most pressing challenges, such as providing affordable energy and clean water, as highlighted by the United Nations Sustainable Development Goals [1]. Membrane technology has been proposed as a potential candidate to help reach these goals thanks to their high energy-efficiency, modularity, compactness, absence of waste creation, and ease of operation, compared to conventional separation techniques [2].

Membrane technology offers an alternative for energy- and solvent-intensive separations, such as distillation, extraction, and chromatography [3]. It is already extensively used in desalination [4], (waste) water treatment [5], and gas separations [6], among others, and is expected to play a major role in future energy conversion and storage devices [7]. Different types of membrane technologies exist, of which nanofiltration (NF) is of particular interest to reject molecules smaller than 1000 g mol^{-1}, such as dyes and micropollutants, down to divalent ions from contaminated water streams [8]. When NF membranes are used to treat organic media, the technology is called organic solvent nanofiltration (OSN) or solvent-resistant NF (SRNF) [2,9]. When small organic molecules of similar size (usually less than 200 g mol^{-1}) need to be separated, organic solvent reverse osmosis (OSRO) membranes can be used [10,11]. OSN/SRNF and OSRO are receiving increased attention in academia and in pharmaceutical, fine chemical, and oil industries, but their progress and understanding is significantly hindered by, amongst others, the data management practices in place [12,13]. Although effort has been directed towards standardizing and optimizing the reporting and measurement practices for OSN/SRNF applications [14], the membrane synthesis and performance data currently present in literature is often scattered, non-standardized, and blocked behind paywalls. These practices endanger accurate data comparison, and hamper the development and understanding of new membrane materials and processes [12].

The recent advances in computational power and digital storage efficiency have enabled the (partial) digitalization of industrial, commercial, and research sectors. This digital transformation has given rise to repositories and large databases that allow researchers to share and analyze information [15]. When the data is additionally made findable, accessible, interoperable, reusable, and open (FAIR/O), machine-actionability, verification, replication, and reuse of data is facilitated [16]. Databases, either generic or domain-specific, play a critical role in developing better theoretical models, identifying suitable materials for specific applications, and answering key research questions [17].

While many research fields have already created and adopted large repositories in the 60s and 70s, such as the Protein Data Bank [18] and the NIST database [19], the development of membrane-focused datasets and databases has only recently begun. Existing databases, such as PolyInfo [20], the Polymer Genome Project [21], the Cambridge Structural Database [22], the Database of Zeolite Structures [23] and the

Metal Organic Framework Database [24], provide information about organic and inorganic materials, but have a limited connection to membranes. In 2012, the first synthetic membrane-related database, the Polymer Gas Separation Membrane Database, was established, but it has not been maintained since 2018 [25]. Recently, a small open access dataset on the upper-bound for OSRO was revealed [26]. The first two large databases that focus on liquid separations with membranes are the OSN Database [27] and the Open Membrane Database (OMD) [28], both established in 2021.

The OSN Database is a free, open access database focusing specifically on OSN/SRNF applications and currently hosts more than 6000 entries with more than 250,000 manually curated or calculated features on solute, membrane, solvent and process parameters [29]. Besides providing freely available data and various data visualization options, the OSN Database also allows machine learning [30] and contains enantiomer separation and solute rejection prediction tools [31]. The OSN Database currently hosts performance data from commercial and custom-made membranes from literature.

The OMD is a free, crowd-sourced, and open-access platform containing FAIR/O data on membrane performance and physicochemical properties, as well as several membrane performance calculators and unit converters [32]. As the initial OMD only contained data on RO desalination membranes, it was coined 'OMD4RO' [28]. The data in the OMD is sourced from peer-reviewed journals, patents, and commercial product datasheets, and can be explored via different visualization tools. The data can also be exported as a text file for further processing. Importantly, the OMD contains an online submission tool that enables users to upload their peer-reviewed data so that the database is up to date with the newest scientific findings.

A new, large dataset containing the initial OSN data from the OSN Database expanded with a new dataset from literature is now revealed. The applied data sourcing, curation, and standardization procedures to obtain this dataset are outlined. The so-called OMD4SRNF, the sister database of the OMD4RO, is hereby inaugurated and contains an online tool for submission of peer-reviewed data by external users. The datasets will be shared between the OSN Database and OMD4SRNF, and both databases will be maintained and kept open access. The data standardization proposed herein follows FAIR data practices to allow more accurate data comparison and meta-analyses within the membrane community and beyond. As all co-authors have committed to deposit their peer-reviewed data of subsequent related research into both databases, the sustainable digitalization of the OSN/SRNF field via FAIR/O data is ensured, together with the sincere hope that every researcher in the field will contribute their data as well.

2. Data sourcing and curation

2.1. General constraints

The OSN Database and the OMD4SRNF focus mainly on NF membrane performance, membrane materials, synthesis parameters, and operational testing conditions in organic media. In procuring data from the literature, certain guidelines were followed to safeguard the scope of the new dataset and respect the intellectual integrity of the reports.

First, only NF membranes tested in organic media are included with a molecular weight cut-off (MWCO) value set between 200 and 1000 g mol^{-1} as the main demarcation criterion [2]. However, some membranes with a MWCO outside of this range are also included, provided that they are part of a series in which at least one membrane possesses a MWCO inside the set range, either within a series of synthesis parameters that were screened, or in at least one solvent or with one solute. These exceptions are made to enable larger meta-analyses in the future. In addition, largely all data available in literature regarding the separation of binary mixtures (mostly based on toluene/1,3,5-triisopropylbenzene), which falls in the OSRO regime, has also been included. However, since OSRO typically focuses on the separation of different solvents or other small molecules (instead of solvent/solute separation more typical of OSN/SRNF), incorporation of more OSRO data into the OMD4SRNF will be addressed in a future database. Furthermore, in some OSRO applications there is no clear distinction between solvent/solute, thus many OSRO membranes are characterized using a separation factor or C_p/C_r (concentration in permeate/concentration in retentate) ratio, rather than with a rejection value. Multicomponent or non-binary OSRO separations data will be therefore addressed in future versions of the database.

Second, all membrane types (*i.e.*, thin-film composite (TFC), thin-film nanocomposite (TFN), integrally skinned asymmetric (ISA), dense, commercial, and inorganic) are included in the dataset. Third, only filtrations performed with solutes in either pure solvents or binary solvent mixtures are incorporated. Membranes tested exclusively in water and water-solvent mixtures are not included at this point to distinguish from aqueous NF and solvent-tolerant NF [33], respectively. These fields are considered separate domains with their own set of challenges and optimization requirements, therefore requiring a separate database. However, aqueous filtrations were included in the database if the same membrane was also tested in organic media.

To enable a better understanding of the membrane synthesis–structure–performance relationships of OSN/SRNF membranes, detailed information on the membrane material, structure, physicochemical properties, synthesis parameters, testing conditions, and membrane performance is also collected. Overall, the aim is to strike a balance between the number of collected parameters, the associated workload, and the database power, while sustaining sufficient future submissions of novel data. The full list of the documented parameters is presented in the Supporting Information. A more detailed 'readme' file, aimed at guiding users through the data submission process, is available online. Below, a general overview of the collected parameters and the rationale behind the selection are given in more detail. Note that, despite our sustained effort to avoid erroneous data from entering the databases, some errors might be present. Any suspicious datapoints can be flagged by external users on the OMD4SRNF, resulting in temporarily removal from the dataset. The founding team will then review these datapoints and resolve or permanently remove them.

2.2. Collected membrane parameters

The membrane parameters that are collected for this dataset include the membrane material and structure, the synthesis method, and the modifications applied during and after synthesis, similar to the OMD4RO [28]. Membrane physicochemical properties, such as thickness, water contact angle, and roughness, are optionally included as well.

Six common membrane categories are considered: ISA, TFC, TFN, inorganic (single-material or composite), and free-standing (*i.e.*, dense, backing-free) materials, and are defined as follows [34]. ISA membranes possess a dense skin supported by a porous substructure, prepared from a single composition via phase inversion (alternatively called phase separation) [35]. TFC membranes consist of a thin, selective layer (either fully organic or fully inorganic) on top of a more open support, typically an ultrafiltration or microfiltration membrane [36]. TFN membranes are structurally similar to TFC membranes but contain a nanomaterial (*e.g.,* metal organic frameworks (MOFs), zeolites, graphene oxide) embedded in the selective layer [37]. For the purpose of this work, the presence of nanomaterials in the top layer is required to qualify as a TFN membrane. Nanomaterials present in other membrane parts are regarded as a modification strategy instead. Inorganic membranes are mainly comprised of an inorganic material, such as ceramics [38], and are subdivided here based on their structure. Inorganic membranes are obtained by the coating of layers with different pore sizes and possibly with different compositions on top of inorganic supports, resulting in either single-material or composite ceramic membranes. Surface functionalization, at the top and/or inside the membrane pore, can be applied as a post-treatment strategy to further tune the membrane performance and characteristics [39]. Lastly, dense, free-standing membranes, were also considered. Although not used in the industrial practice, these membranes are of crucial importance to understand fundamental transport aspects and develop structure-property correlations needed to design membranes and processes exhibiting enhanced permeability, rejection, and long-term durability [40,41]. Note that for certain membrane preparation methods, appointing a membrane category is ambiguous *e.g.,* a selective layer grafted onto an ISA membrane. For ambiguous cases, the classification presented in the source material is preferentially followed. Alternatively, a membrane classification guide is also available in the 'readme' file.

A set of synthesis parameters was collected depending on the used membrane synthesis method, including phase inversion and interfacial polymerization (IP) (Fig. 1). Although the phase inversion process is known to be very sensitive to a plethora of parameters [34,35], not all synthesis conditions are always reported by default in literature [14]. Therefore, a careful selection of relevant synthesis parameters was made, including polymer chemistry, polymer concentration and solvent (mixture) of the dope solution, non-solvent (mixture), additive nature and concentration, and casting thickness. For inorganic membranes, only the chemistry was included. For membranes derived from IP, information on the aqueous and organic phase, and the monomer nature and concentration were collected. This is to, among other objectives, further guide the efforts directed towards the synthesis of top layers to achieve a better performance than obtainable with conventional polyamide-based top layers. The monomers and additives were specified via their simplified molecular-input line-entry specification (SMILES) string (Table S5). Next to IP, other thin-film deposition methods like spin coating, dip coating, grafting, spray coating, kiss coating, layer-by-layer deposition, electrospray coating, casting, pressurized filtration, and vacuum filtration were documented as well. Additional parameters that are collected for TFN membranes were the embedded nanomaterial name, its concentration and position during synthesis (*e.g.*, its dispersion either in the water phase or in the organic one when using IP). For TFC and TFN membranes, support layer parameters are collected as well, according to their support structure (*i.e.*, ISA, inorganic, fibrous or commercial). Irrespective of the membrane structure, information on the membrane post-treatment strategies, including the SMILES string of the chemical agents and their concentration, was also documented.

2.3. Collected testing parameters

Other membrane applications, like RO or gas separations, are defined by a limited set of relevant feed compositions, allowing the compilation of trade-off plots and the accompanying upper bound relationship for membrane performance, of which both fields have greatly benefitted [28,42,43]. Such convenient benchmarking tools have thus far been absent for the field of OSN/SRNF due to the quasi-infinite variety of used solute(s) and solvent(s), and the complexity of the resulting solute–solvent–membrane interactions. This complex interplay hinders direct comparison of membrane performance between different solvents, membrane chemistries, different solutes of similar molecular weight (MW), and even between different operational conditions (*i.e.*, solute concentration, temperature, transmembrane pressure, detection methods) [14,44,45]. In an attempt to enable more accurate membrane comparison, detailed information on the membrane testing conditions was collected. Parameters related to the membrane rejection for a specific solute (mixture) used in the feed solution include the solute concentration, MW and category, as defined in ref. [45]. Solute structures were represented by their unique SMILES string, which is

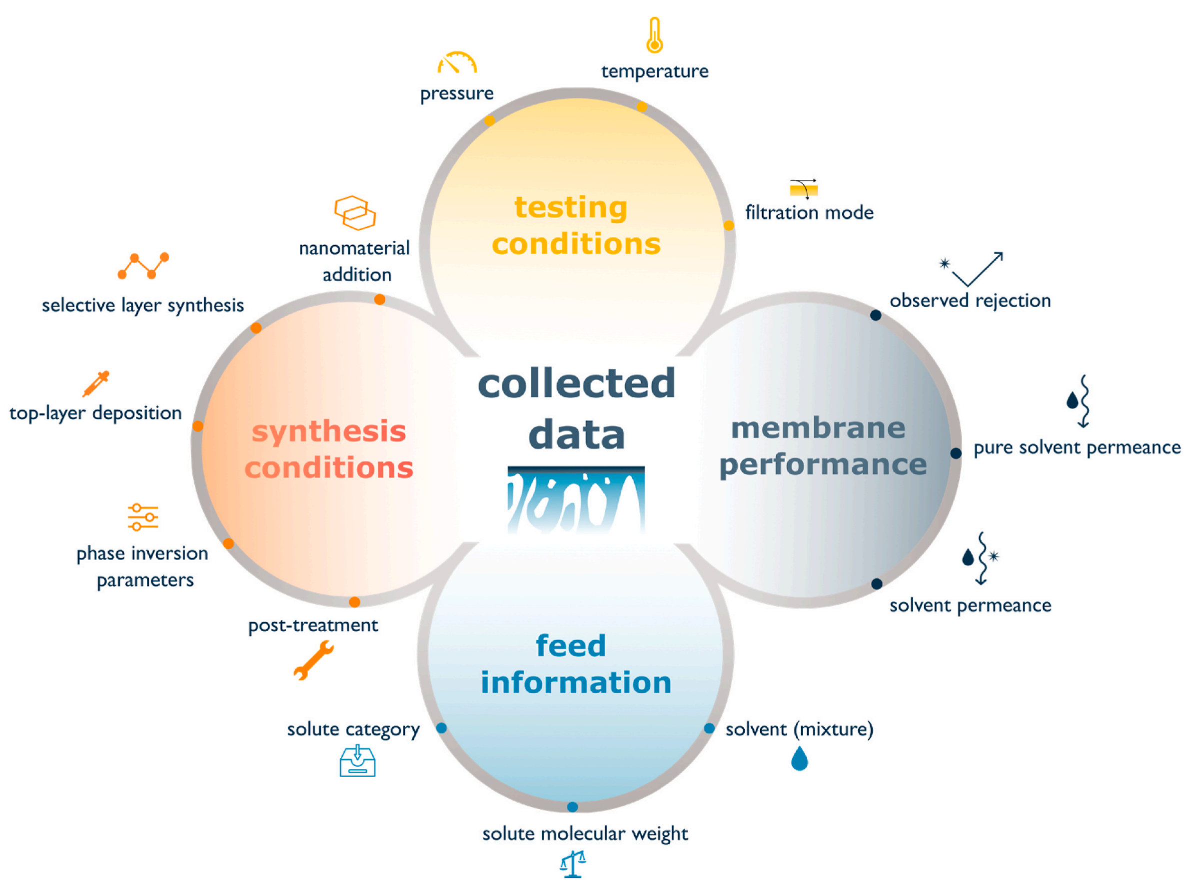

Fig. 1. Overview of the different categories for which data was collected as input for the dataset. The main categories are synthesis conditions, feed information, testing conditions, and membrane performance. The most important parameters per category are also shown.

the default database representation for molecular structural data. SMILES also allows to calculate various molecular properties using software packages like Mordred and RDKit Python packages, as currently done in the OSN Database [30]. Several molecular descriptors and physicochemical properties related to the solute and solvent of interest are also available on the OMD4SRNF (Supporting Information). These descriptors, such as molar volume and dipole moment, were included to help better understand certain observations, but are by no means meant to be exhaustive. Next to solute information, data on other important experimental conditions, such as filtration mode (*i.e.*, cross-flow and dead-end), temperature, transmembrane pressure, and the nature of the solvent (mixture) were also collected.

2.4. Collected membrane performance parameters

To characterize membrane performance, observed solute rejection (R_{obs}, further denoted as R, Eq. S(1)), pure solvent permeance (*i.e.*, measured in the absence of solutes), solvent permeance (*i.e.*, measured in the presence of solutes), and MWCO values were collected, only if explicitly reported in the source material (Eq. S(2)). Note that R_{obs} can differ from the real solute rejection, R_{real}, due to concentration polarization and fouling. However, due to the limited availability of R_{real} in the literature, only R_{obs} is documented. As the specific mechanisms governing solvent transport in nanofiltration membranes is not yet completely understood, only these four performance parameters were collected [46–48]. Despite recognizing the potential significance of fouling in some OSN/SRNF applications, no parameters related to these phenomena are collected at this point due to the very limited number of available studies [49–51].

3. Database content and functionalities

3.1. Database content

The OSN Database and the OMD4SRNF are continuously growing databases, with the data on both platforms being periodically updated. Both will remain separately accessible free of charge to exploit the data via the different tools that exist on each platform. The OSN Database hosts existing datasets (*i.e.*, Datasets 1–4) [27,52–54], and an entirely new dataset (*i.e.*, Dataset 5) curated for the purpose of this work and for the inauguration of the OMD4SRNF (Table 1). Now all 5 datasets are available on both databases. Dataset 5 consists of 294 peer-reviewed articles, published between 2000 and 2024, and compiled from a literature search across 7 search engines (Supporting Information, Table S8). Some additional peer-reviewed manuscripts that fulfill the general dataset requirements but that were not found through the literature search, were provided by the authors and were also incorporated. The datasets on the OSN Database and the OMD4SRNF fall under a CC-BY-4.0 and a CC BY-NC-4.0 license, respectively.

3.2. Online submission tool & database maintenance

The OMD4SRNF contains an online submission tool that allows external users to deposit their peer-reviewed data in the database in a step-by-step fashion, and free of charge. The required input follows the same structure as outlined above, with a distinction made between mandatory and optional fields. Only submissions possessing a valid DOI that are published in a peer-reviewed journal are eligible for submission to the OMD4SRNF [28]. All data deposited by external users is checked for any errors by the OMD4SRNF team and then published on both the OMD4SRNF and the OSN Database. Additionally, a GitHub mirror repository of the dataset is available as an open-access backup.

The sustainability of the OMD is currently directly dependent on the involvement of the membrane community by uploading their data. While the commitment of all co-authors to supply their future work is a step in the right direction, on-boarding the entire field of OSN/SRNF will require a shift in the academic structures in place so that contributing to the common good through, amongst others, FAIR/O data management is supported and domain-specific databases are valued [17,55]. Several concrete actions are currently undertaken to advocate for and accelerate this shift to ultimately ensure database sustainability. While the maintenance of the OMD and the OSN Database is currently ensured by the founding teams of the respective databases, an international call for so-called OMD ambassadors will be launched to further involve the field. These ambassadors will be asked to encourage data supply and revise uploaded data, similar to associate editors of journals. In addition, the OMD is advocating to partner up with journals related to membrane technology, as they have the leverage to enforce data publication in an open repository. The OMD can then be populated from such a repository by data discovery tools, ensuring the longevity of the OMD. Lastly, sustained involvement of the membrane societies would also be befitting as the aim of the OMD is to become a database-hub for the entire field of membrane technology. Action is currently being undertaken to include more detailed synthesis information on ceramic membranes and hollow fiber membranes, and to expand the OMD from RO and OSN/SRNF to, amongst others, gas separation and ion-exchange membranes.

3.3. Data processing interface

Dataset 1-5 can be explored on the OMD website through an interactive chart featuring various search functionalities (Fig. 2). Users can manipulate the chart layout to compare membrane properties, synthesis parameters, filtration conditions, and membrane performances. The x and y axes (in log-normal or linear scale) can be freely selected from a range of numerical properties (*e.g.,* (pure) solvent permeance, R_{obs}, MWCO, polymer concentration in dope solution, filtration pressure and temperature, report year). The legend display can be altered between a selection of quantitative (*e.g.,* report year, (pure) solvent permeance, R_{obs}) and non-quantitative (*i.e.,* selective layer chemistry and membrane structure) properties. At the time of writing, 21 different filter types can

Table 1
Information on the different datasets hosted by the OSN Database and the OMD4SRNF. A datapoint is one unique value either collected from literature, or calculated from literature data (*e.g.*, solute MW calculation from solute structure, permeance calculated from pressure and flux). When the experimental parameters were kept constant throughout a dataset, they were not considered as datapoints. An entry corresponds to a unique membrane filtration. A dataset is a compilation of datapoints. A database is a collection of datasets. Dataset 5 is based on available data as per April 2024. Note that datapoint inclusion on each platform (OMD4SRNF and OSN database) depends on the respective database requirements.

Database	Dataset	Membrane types	No. of datapoints	No. of entries	Membrane chemical structure	Launch year	Ref.
OSN Database	Dataset 1	Commercial	38,430	4,690	No	2021	[54]
	Dataset 2	Commercial	2,840	417	Yes	2022	[27]
	Dataset 3	Commercial	9,336	1,167	Yes	2023	[53]
	Dataset 4	Commercial, tailor-made ISA	15,504	1,938	Yes	2023	[52]
	Total (1–4)	Commercial, tailor-made ISA	66,110	8212		2021–2023	
OMD4SRNF & OSN Database	Dataset 5	Commercial, tailor-made membranes	231,258	5,006	Yes	2024	This work
	Total (1–5)	Commercial, tailor-made membranes	297,368	13,218		2021–2024	

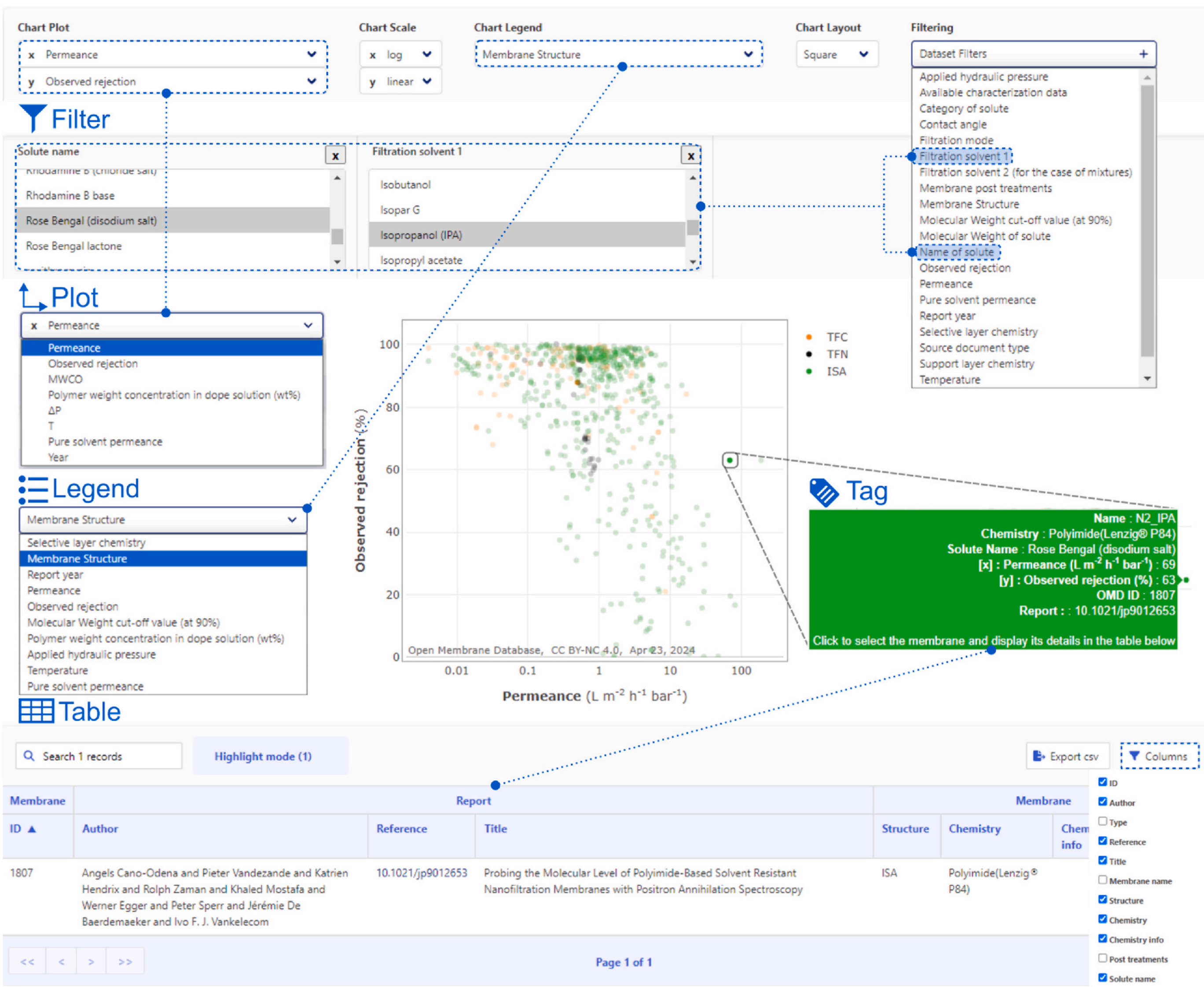

Fig. 2. Visual representation of the user interface for data exploration on the Open Membrane Database (OMD). Different fields used for chart manipulation, filtering, and data retrieval are highlighted. ‘Plot’ and ‘Legend’ fields are used to manipulate the chart layout. Data can be extensively filtered using the ‘Filter’ fields. Selecting a datapoint from the chart will prompt a pop-up ‘Tag’ to display additional information. Selected datapoints are displayed in a filterable ‘Table’ at the bottom of the page, where different properties can be selected. The data table can be exported as a csv file. For illustration purposes, this snapshot image from the OMD4SRNF has been modified for clarity.

be applied simultaneously to narrow down the displayed data, allowing facile data analysis. Numerical filters (*e.g.,* solute MW) allow specification of a minimum-maximum value range, while non-numerical filters (*e.g.,* filtration mode) permit selection of the desired value from a list. Highlighting individual datapoints prompts a pop-up tag to display, where applicable, the datapoint name, the membrane chemistry, solute name, database ID, digital object identifier (DOI) of the source document, and the x and y coordinates. Alternatively, lasso or rectangle selection tools allow highlighting multiple datapoints at once. All selected points are tabulated at the bottom of the page together with additional information that can be selected by the users via the displayed columns. The database plot and the data table can be exported as an image (.png) and a data file (.csv), respectively. Note that the displayed or exported information can potentially consist of a smaller number of datapoints compared to the entire dataset, as not all collected parameters are always disclosed in the source material nor are they applicable to all membrane categories.

3.4. Brief analysis of collected data

As per April 2024, the newly compiled dataset (*i.e.*, Dataset 5, Table 1) contains data gathered from 294 publications from 2000 to 2024, adding up to 5006 datapoints (Fig. 3a). A brief analysis of the dataset is given here to highlight some general observations about the field of OSN/SRNF and to spur the field to conduct more in-depth meta-analyses with *e.g.*, machine learning tools. More than 7000 crossflow and 4500 dead-end filtration measurements are included (Fig. 3b), of which more than one third has a rejection value of >90 % (Fig. 3c). The dataset also consists of a wide range of solutes, as demonstrated by the high solute MW coverage (Fig. 3d), and a large set of chemistries, both for the active layer as well as for the support layer (Fig. 3e–h). Polyamides dominate the active layer chemistry while polyacrylonitrile is the most common support chemistry. The most prevalent membrane structure in the dataset is ISA, followed by TFC and commercial membranes (Fig. 3f). By showcasing the monomers used during IP for the synthesis of TFC membranes in a tree manifold approximation and

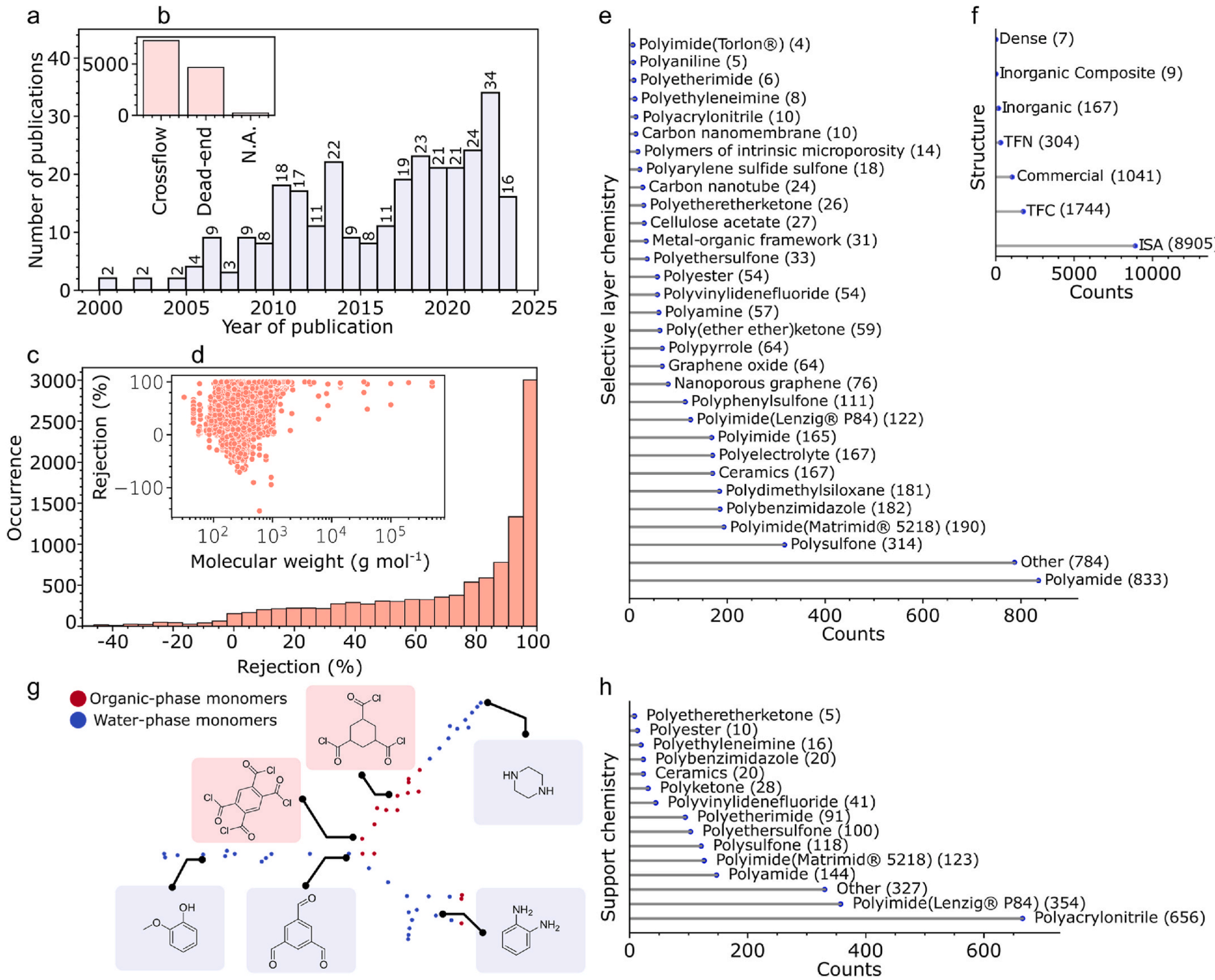

Fig. 3. High-level summary of dataset 5 curated for this work. **a**) The number of publications over the years (2000–2024) with their yearly count. **b**) The crossflow versus the dead-end filtration ratios. N.A. indicates that the information was not available in the source document. **c**) Rejection histogram. **d**) Rejection as a function of the molecular weight. **e**) Different membrane structure types and their occurrence. 'Other' indicates that the chemistry was not available in the predefined options and had to be specified by the user. **f**) Different membrane structures and their occurrence. **g**) TFC monomer types visualized on a TMAP diagram. Structurally similar monomers are closer to each other. **h**) Different support structures and their occurrence.

projection (TMAP) plot, the molecular structural similarity of the used monomers is discernible (Fig. 3g). The mostly used monomers are depicted as well. The diverse and comprehensive dataset opens up the possibilities for future data exploration and analysis to achieve a better understanding of membrane synthesis-structure-performance relationships and to accelerate the development of novel membrane materials. The filtration data can also be used to design filtration systems for specific separations, for example by using the Open Membrane System Design Tool [56] or PROSYN® Membranes [57].

4. Conclusions

With this initiative, the OSN/SRNF community stands united and presents a data standardization and sharing approach that enables the sustainable digitalization of the field. A new dataset was curated, compiling 294 peer-reviewed articles ranging from 2000 to 2024, and is available on the OSN Database, as well as on the newly inaugurated OMD4SRNF. Membrane synthesis parameters (including the membrane material, structure, support and top layer chemistry, monomers, solvents, additives, and modifications), testing conditions, and membrane performance are documented in detail. This large and diverse dataset, consisting of more than 5006 unique membrane filtrations as per April 2024, allows investigating the synthesis-structure-performance relationship of OSN/SRNF membranes from a variety of angles, enabling *e.g.*, meta-analyses, machine actionability, and statistical data interpretation. External users are encouraged to submit their latest peer-reviewed data via the online submission tool available on the OMD4SRNF, which is then directly linked to the OSN Database. The commitment of all authors to supply their future work to the databases is already a significant acceleration in the direction of large and FAIR/O data, which paves the road for increased understanding and innovation in the field of OSN/SRNF.

CRediT authorship contribution statement

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Gergo Ignacz: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Scout Caspers:** Writing – review & editing, Data curation. **Robin Dhondt:** Writing – review & editing, Data curation. **Marie Lenaerts:** Writing – review & editing, Data curation. **Nathalie Lenaerts:** Data curation, Writing – review & editing. **Sareh Rezaei Hosseinabadi:** Writing – review & editing, Data curation. **Ines Nulens:** Writing – review & editing, Data curation. **Guy Koeckelberghs:** Writing – review & editing, Funding acquisition. **Yi Ren:** Writing – review & editing, Data curation. **Ryan P. Lively:** Writing – review & editing, Data curation. **Murielle Rabiller-Baudry:** Writing – review & editing, Data curation. **Ki Min Lim:** Writing – review & editing, Data curation. **Nazlee Ghazali:** Writing – review & editing, Data curation. **Joaquin Coronas:** Writing – review & editing, Data curation. **Milan Abel:** Writing – review & editing, Data curation. **Matthias Wessling:** Writing – review & editing, Data curation. **Mirko Skiborowski:** Writing – review & editing, Data curation. **Adam Oxley:** Writing – review & editing, Data curation. **Seok Ju Han:** Writing – review & editing, Data curation. **Andrew Livingston:** Writing – review & editing, Data curation. **Zhuan Yi:** Writing – review & editing, Data curation. **Congjie Gao:** Writing – review & editing, Data curation. **Kecheng Guan:** Writing – review & editing, Data curation. **Ralph Rolly Gonzales:** Writing – review & editing, Data curation. **Hideto Matsuyama:** Writing – review & editing, Data curation. **Srivatsa NM. Bettahalli:** Writing – review & editing, Data curation. **Jeffrey R. McCutcheon:** Writing – review & editing, Data curation. **Farzaneh Radmanesh:** Writing – review & editing, Data curation. **Nieck E. Benes:** Writing – review & editing, Data curation. **Akbar Asadi Tashvigh:** Writing – review & editing, Data curation. **Qing Fang:** Writing – review & editing, Data curation. **Kaisong Zhang:** Writing – review & editing, Data curation. **Guining Chen:** Writing – review & editing, Data curation. **Wanqin Jin:** Writing – review & editing, Data curation. **Yatao Zhang:** Writing – review & editing, Data curation. **Chun-Xu Zhang:** Writing – review & editing, Data curation. **Mei-Ling Liu:** Writing – review & editing, Data curation. **Shi-Peng Sun:** Writing – review & editing, Data curation. **Anita Buekenhoudt:** Writing – review & editing, Data curation. **Chen Zhao:** Writing – review & editing, Data curation. **Bart Van der Bruggen:** Writing – review & editing, Data curation. **Jeong F. Kim:** Writing – review & editing, Data curation. **Lucas C. Condes:** Writing – review & editing, Data curation. **Matthew T. Webb:** Writing – review & editing, Data curation. **Michele Galizia:** Writing – review & editing, Data curation. **Banan Alhazmi:** Writing – review & editing, Data curation. **Lakshmeesha Upadhyaya:** Writing – review & editing, Data curation. **Suzana P. Nunes:** Writing – review & editing, Data curation. **Dae Woo Kim:** Writing – review & editing, Data curation. **Henrik Schröter:** Writing – review & editing, Data curation. **Udo Kragl:** Writing – review & editing, Data curation. **Sven Störtte:** Writing – review & editing, Data curation. **Andreas J. Vorholt:** Writing – review & editing, Data curation. **P. Zeynep Culfaz-Emecen:** Writing – review & editing, Data curation. **Marie-Alix Pizzoccaro-Zilamy:** Writing – review & editing, Data curation. **Louis Winnubst:** Writing – review & editing, Data curation. **Alexey Yushkin:** Writing – review & editing, Data curation. **Alexey Volkov:** Writing – review & editing, Data curation. **John Chau:** Writing – review & editing, Data curation. **Kamalesh K. Sirkar:** Writing – review & editing, Data curation. **Shao Lu:** Writing – review & editing, Data curation. **Gyorgy Szekely:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Ivo Vankelecom:** Writing – original draft, Resources, Project administration, Funding acquisition, Conceptualization. **Rhea Verbeke:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

the data is openly available on the Open Membrane Database and the OSN Database

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.memsci.2024.123356.

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