Dielectrophoresis (DEP) is a selective electrokinetic particle manipulation technology that is applied for almost 100 years and currently finds most applications in biomedical research using microfluidic devices operating at moderate to low throughput. This paper reviews DEP separators capable of high-throughput operation and research addressing separation and analysis of non-biological particle systems. Apart from discussing particle polarization mechanisms, this review summarizes the early applications of DEP for dielectric sorting of minerals and lists contemporary applications in solid/liquid, liquid/liquid, and solid/air separation, for example, DEP filtration or airborne fiber length classification; the review also summarizes developments in DEP fouling suppression, gives a brief overview of electrocoalescence and addresses current problems in high-throughput DEP separation. We aim to provide inspiration for DEP application schemes outside of the biomedical sector, for example, for the recovery of precious metal from scrap or for extraction of metal from low-grade ore.

1 Introduction

Dielectrophoresis (DEP) describes the motion of particles due to the action of a non-homogeneous electric field on the particles’ induced dipole. The DEP force depends, among other factors, on the particle volume, shape, and material. This allows the application for selective particle separators that require neither particle charge nor labeling. Although the effect was already commercially applied almost 100 years ago [1], it was not until 1951 that Herbert Pohl first mentioned the word “Dielectrophoresis” in his seminal research work [2]. First applied for the separation of carbon black from polyvinyl chloride (PVC) in di-isopropyl ketone, a paper published in Science [3] by Pohl and his master’s student Ira Hawk on the separation of live and dead yeast cells in inhomogeneous electric fields motivated many following DEP research efforts. In the end of the 1980s, several groups started replacing the then conventional macroscopic wire and sheet electrodes with microelectrodes manufactured in a cleanroom using thin-film technology. Subsequently, dielectrophoresis quickly became a predominantly microfluidic tool: When keeping particle and medium properties constant, the movement depends mainly on the square of the applied field (Eq. 1). This term has units $V^2/m^3$. The $m^{-3}$-dependence makes it quite clear that a strong force requires a small distance between the employed electrodes. Though some concepts and applications of large scale separators have been reported, the majority of DEP applications address analysis of small samples while maintaining a high selectivity and efficiency; a task which is ideally suited for microfluidic lab-on-a-chip applications, which became popular in the 1990s. A historical overview of the development of DEP is available in two independent reviews by Ron Pethig [4] and Mike Hughes [5]. Today, DEP is an academically established technique. Despite its potential for solving challenging industrial separation tasks, such as concentration of valuable minerals from low-grade ore or recycling of electronic waste for environmentally benign processes, nowadays it is almost exclusively applied in the fields of analytical and bioanalytical chemistry. This is because it is capable of bridging a gap left by other established techniques, that is, DEP is capable of label-free separation of biological cells according to the ion content in the cytoplasm, the membrane capacitance, or surface proteins.
Biomedical DEP applications have been summarized and discussed in many fine reviews [6–12]. Here, we review the DEP application for non-biological particle systems. The main driver is the wish to apply dielectrophoresis as a force in industrial-scale separation processes to solve problems not having a solution so far or only a non-economically reasonable solution using existing technologies. Many older reports discuss the application of DEP for the separation of non-biological particle systems. They nowadays, however, are in the shadow of the vast majority of DEP biomedical applications. This specifically excludes the very active research on electric field-assisted assembly of nanowires and nanoparticles for the production of functional nanodevices and nanomaterials, which is out of this work’s scope.

This review is organized as follows: Firstly, a brief introduction on the theory of dielectrophoresis will be given. We have no intention to replace the excellent textbooks on the topic and thus keep this section rather short. Then, the current understanding in polarization mechanisms important for non-biological particles will be reviewed before briefly discussing possible device designs for DEP. This is followed by a section discussing technical applications of DEP in various fields. We will see that the application of dielectrophoresis for solid particle separation at industrial or at least preparative scale poses some problems when using aqueous suspensions. This is because high voltages need to be applied for high throughput separation, either because of large electrode distance or because strong forces are required to overcome the drag force. This can result in electrolysis, Joule heating, and bubble formation [13]. Consequently, many reports in this review use non-conducting organic liquids as suspension, such as oil or ethanol, allowing application of much higher voltages [14,15]. We will review some of our own and other groups’ work on DEP filtration, which is a technology that has the potential for high-throughput application in aqueous suspensions. Many promising applications of DEP-based separation of non-biological particles will be presented. Those include the enrichment of low-concentration valuable products, the separation of precious metals from waste streams, the separation of minerals (including rare earth elements and the separation of metals from low-grade ore) according to their polarizability, or the continuous fractionation of high-value products at high accuracy (such as carbon nanotubes). The review further addresses applications of DEP for the separation and classification of airborne particles and liquid-in-liquid droplets and as a force to reduce membrane fouling in filtration applications. For the sake of completeness, a brief overview of demulsification (electrocoalescence) will be given.

2 Theory

This section will introduce some theoretic concepts of dielectrophoresis. Because this review is aimed at being a practical guide, for brevity, we will thus only scratch the surface of the underlying theory. For a more general view, we like to refer the reader to the textbooks covering the topic [16–18].

2.1 DEP Force calculation

When a charged particle is placed in an electric field (be it homogeneous or inhomogeneous) it experiences an electrophoretic force, which comes, in a crude approximation, from the electrostatic Coulomb force acting on the charge. In reality, the electrophoretic motion is widely described by the well-known Helmholtz-Smoluchowski equation (which relates the electrophoretic force to the particle’s \( \zeta \)-potential). In the case of a viscous fluid, the electrophoretic force will result in a net motion of the particle. When the exciting field is oscillating (i.e., an alternating current, ac, field), the particle will (in most cases) only oscillate with an amplitude defined by the \( \zeta \)-potential and frequency and amplitude of the applied field. If the particle is uncharged or has a \( \zeta \)-potential close to zero, it does not experience an electrophoretic force.

Generally, dielectrophoresis describes movement of charged or uncharged particles in inhomogeneous electric fields. It does not directly depend on the charge (we will later see that it indirectly does) but rather on the particle’s relative polarizability in the given medium. The dielectrophoretic force is due to the action of an inhomogeneous electric field on an induced dipole (or multipole). A particle in an electric field will polarize, i.e., charges are separated across the particle’s length scale. As a consequence, the particle will carry charges of opposing signs but equal magnitude on each side. These charges experience Coulomb forces due to the exciting field. Since the charges are of equal magnitude, the forces cancel each other out in the case of a homogeneous exciting field. When the exciting field is inhomogeneous, the force on one side is slightly smaller resulting in a net force on the particle. When the particle is not fixed, this will give rise to a dielectrophoretic motion. The point-dipole model [19] assumes a homogeneous spherical particle of radius \( a \) that is small in comparison to the length scale of the applied field inhomogeneity. Then, the time-averaged DEP force in an ac electrical field of amplitude \( E \) reads

\[
\langle F_{\text{DEP}} \rangle = \pi \varepsilon_m \varepsilon_0 a^3 \text{Re}[K_{\text{CM}}] \nabla |E|^2. \tag{1}
\]

where \( \varepsilon_m \) is the relative permittivity of the medium, \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \) is the vacuum permittivity, and \( K_{\text{CM}} \) is the particle’s Clausius-Mossotti factor. Its real part gives the particle's relative polarizability in the medium and determines the movement direction of the particle in the field. It is frequency dependent and given by

\[
K_{\text{CM}} = \frac{\varepsilon_p - \varepsilon_m^*}{\varepsilon_p + 2\varepsilon_m^*} \tag{2}
\]

with the complex permittivity of the particle or medium (subscript P or M, respectively) \( \varepsilon^* = \varepsilon_0 \varepsilon_i - \varepsilon_m^2 / \omega \), the relative permittivity \( \varepsilon_i \), the conductivity \( \sigma = j \omega \varepsilon_0 \), and the angular frequency \( \omega = 2\pi f \). The frequency \( f \) of the applied ac field.

Upon application of the electric field, not only the particle but also the suspension surrounding the particle will polarize. This polarization manifests itself in polarization...
charges that accumulate on the particle’s surface in both the particle itself but also in the liquid medium (Fig. 1A). This is termed Maxwell–Wagner interfacial polarization. The charges accumulating on the liquid side of the interface will be of opposite sign compared to the charges that accumulate on the particle side. The (complex) permittivity defines how well a material (particle or medium) will polarize in response to an electric field. Thus, the amount of charges inside and outside of the particle are (in most cases) not equal. They depend on the complex permittivity of the particle or medium, respectively. When the total polarization charge outside of the particles is larger, the particle is less polarizable than the suspension and \( K_{CM} \) is negative. Then, the particle experiences negative DEP (nDEP, Fig. 1A, blue particle) and it will move against the field gradient away from local field maxima. Conversely, when the charge on the particle side of the boundary is larger, \( K_{CM} \) is positive, the particle is better polarizable than the suspension, and it experiences positive DEP (pDEP, Fig. 1A, red particle). It will then move toward local electric field maxima. There is both a dielectric component, i.e., a component that is caused by slight shifts of immobile charges from their equilibrium position, and a conduction component to the polarization of a material. Depending on the frequency, the overall polarization is either dominated by the dielectric contribution (\( \rho_0 \varepsilon^\ast \varepsilon \)) or by the conductive contribution (\( \sigma \)). By definition, both the real and imaginary parts of \( K_{CM} \) are bound between \(-0.5 \) and \( 1 \). The imaginary part gives the loss that occurs during polarization (for example as heat). Upon inspection of Eqs. (1) and (2) we note that:

- the DEP force vanishes in case of a homogeneous field \( \nabla |E| = 0 \);
- the DEP force vanishes in case of \( \text{Re}[K_{CM}] = 0 \), which is when \( \varepsilon_\ast^\ast = \varepsilon_\ast^\ast \). The frequency at which this occurs is the cross-over frequency \( \nu_0 = \frac{1}{2 \pi \sigma_0 + \mathrm{Im} \varepsilon_\ast} \) at which the particle experiences no net polarization in the suspension.
- The Clausius-Mossotti factor \( K_{CM} \) has two frequency limits depending on the particle and medium properties. At low frequencies, the behavior is frequency independent and dominated by charge conduction and \( K_{CM} = \frac{\sigma_0 - \varepsilon_\ast}{\sigma_0 + \varepsilon_\ast} \). At high frequencies, the behavior is entirely dominated by dielectric polarization and \( K_{CM} = \frac{\varepsilon_\ast - \varepsilon_\ast^\ast}{\varepsilon_\ast + \varepsilon_\ast^\ast} \). In reality, lossy dielectrics (what we are dealing with here) experience Debye relaxations. Thus, \( \varepsilon_\ast \) is in fact frequency-dependent and shows variations at GHz frequencies and above, which we can safely ignore here as, due to technical reasons, DEP is usually performed at frequencies substantially smaller than \( 10^9 \) Hz.

The application of (high) voltages across electrodes in aqueous suspensions is inevitably linked to side effects which can dominate the particle behavior; these effects include Joule heating-induced fluid vortices, ac electroosmosis, electrochemical reactions, and bubble formation. In addition, the polarization of a particle causes attractive forces on neighboring particles leading to particle-particle interaction. This usually results in the formation of so-called pearl chains parallel or perpendicular to the applied field that can include particles that experience both pDEP and nDEP (see Ref. [17], Fig. 4.10). This interaction will decrease separation efficiency because properties of chains are different from single particles.

---

**Figure 1.** (A) Particle polarization in an inhomogeneous field (in this example generated by a wire-plate electrode arrangement, in which the maximum electric field is found at the smaller electrode and a field gradient points from left to right). When a particle is better polarizable (red) than the surrounding medium, the polarization charges inside the particle are larger than outside, the dipole will point in the direction of the field and the particle experiences pDEP. Contrary, when a particle is less polarizable, the charges on the outside are larger than on the inside; the dipole will point in the opposite direction (against the applied field) and the particle will experience nDEP. Note: In an ac field, all charges reverse sign each half-cycle, the resulting relationships and forces will be the same. (B) Typical dipole coefficients (\( \text{Re}[K_{CM}] \)) of a spherical metal (green) and polystyrene (red) particle and of a red blood cell. Metal and polystyrene particles are immersed in 0.01 mM KCl solution (\( \varepsilon_\ast = 1.5 \mu \text{s/cm} \)) and have \( \sigma_\ast = 1.5 \mu \text{m} \) and \( \varepsilon_\ast = 5 \mu \text{m} \) radius, resp. For the plastic particle \( \varepsilon_\ast = -130 \text{mV} \). The metal particle is assumed to have a double layer capacitance \( \varepsilon_\ast = 0.1 \text{F/m}^2 \). For the plastic particle, the combination of the DS model and the MWO model (i.e., the other model takes over at the intersection point) gives the full polarization coefficient. The red blood cell (blue) is immersed in a \( \varepsilon_\ast = 30 \mu \text{s/cm} \) solution and is assumed to have a radius \( a = 5 \mu \text{m} \). Full parameters and equations are given in the Supporting Information Section S2.
particles [23] and because both target and nontarget particles become trapped in chains. Further, conductive particle chains can bridge the electrodes leading to short circuits [22]. The effect was modeled using simulation and experiments [24–26]. Naturally, particle-particle interaction increases with increasing particle concentration (i.e., reduced particle-particle distance). For example, Gascoyne and Shim state that an average cell spacing of three cell diameters is required for an equilibrium field-flow fractionation device to operate effectively [21].

2.2 Multipole model and Maxwell stress tensor

Equations (1) and (2) are derived assuming a homogeneous spherical particle that is small enough to assume that the field does not change considerably over the diameter of the particle. Then, the induced polarization in the particle will take the form of a dipole. Of course, assuming a homogeneous excitatory field contrasts the DEP requirement of inhomogeneous fields, but the assumption delivers sufficiently precise results for many applications. When the field changes considerably over the diameter of the particle, or if the particle is not spherical, the induced polarization differs from a dipole. Then, we cannot simply calculate the higher-order multipoles analytically. It is possible to extract higher-order multipoles from a numerical calculation of the electric field around the particle [27,28]. Then, it is possible to calculate a more precise approximation of the DEP force employing higher derivatives of the electric field [28–30]. In the special case of ellipsoids, it is possible to analytically derive the dipole moment [31,32], however, higher-order multipoles might considerably deviate from zero and neglecting them can cause errors in the DEP force calculation [30].

A precise calculation of the force is also possible without considering the multipolar approximation by calculating the electric field in the presence of the particle and then using the Maxwell stress tensor (MST) to obtain the force [33,34]. This is considered the most rigorous approach to deriving field-induced forces. Zhao et al. used a volumetric integration method in order to obtain accurate descriptions of the DEP force [35]. A comparison of the MST method against the effective moment force calculation is given in Refs. [30,36,37].

To calculate the polarization of non-homogeneous particles, with the most prominent example being biological cells, researchers usually refer to the shell model ([17], section 3.2.3). Here, in an onion-like fashion, the particle is considered as a sequence of shells. The consequence is that cells can have more than one crossover frequency, as every material interface shows a Maxwell–Wagner interfacial polarization mechanism. Usually—of course this depends on the medium properties—cells show nDEP at low frequencies, pDEP at intermediate frequencies, and again nDEP at very high frequencies (Fig. 1B, blue line).

2.3 Polarization of micron and submicron non-conducting particles

Most non-conducting micron, submicron, and nanoparticles will, depending on the suspension conductivity, show positive DEP at some frequencies, although Equation (2) would predict a negative DEP response almost independent of frequency. This has been observed extensively for polystyrene (PS) particles [38] but also for other nonconducting particles such as silica [39]. The reason for this anomalous behavior lies in the contribution of the double layer (DL) to the overall conductivity of the particle. When suspended in an electrolyte suspension, ions are attracted by the charged surface, and form an interfacial double layer. The rather conductive double layer will polarize under the application of an electric field.

Two main methods are used to describe the polarization behavior of a particle that is significantly influenced by the double-layer conductance. The generally accepted methodology is the Maxwell–Wagner–O’Konski (MWO) model, which adds a surface conductance term to the particle’s bulk conductivity. It is described, for example, in the influential work of Ermolina and Morgan [40]:

$$\sigma_p = \sigma_s + \frac{2K_0}{a}. \quad (3)$$

Then, in a very simple picture, the DL forms a conductive shell around the particle that increases its net conductivity. Here, \(K_0\) is the surface conductance and \(\sigma_s\) is the bulk conductivity. If \(\sigma_s\) is very small, the behavior is entirely dominated by the DL conductivity. \(K_0 = K_{D} + K_{S}\) is usually split into the Stern layer conductance \(K_{S}\), which is assumed as 1 nS almost independent of particle size and medium conductivity [40], and the diffuse layer conductance \(K_{D}\), that increases with medium conductivity. The conduction of charge through the bound Stern layer occurs in a thin layer of finite thickness. The charges in the diffuse layer, however, are distributed in an ionic cloud. The size of the cloud depends on the medium conductivity: The higher the conductivity, the smaller (denser) the cloud, which can be calculated using the Debye length \(\xi^{-1}\). The electric field creates an electro-osmotic force on the charge cloud so that it deforms, compressing it on one side and elongating it on the other. \(K_{D}\) only takes appreciable values for large medium conductivities (roughly \(10^{-2}\) to \(10^{-1}\) S/m and particle \(\zeta\)-potentials \(|\zeta| > 100\text{mV}\) and could be calculated using Equation (S1) in the Supporting Information. In case \(K_0\) is sufficiently large and \(a\) sufficiently small, Equations (2) and (3) predict pDEP at low frequency and nDEP at high frequency. We expect pDEP at low frequency up to a radius of \(a < 2K_0/\sigma_s\). For \(K_0 = 1\text{nS}\) (thus neglecting the diffusion layer term) and 0.01 mM KCl \(\sigma_s = 1.5\mu\text{S/cm}\), this results in pDEP for polystyrene particles up to a radius of 13.3 \(\mu\text{m}\).

It has been discussed that the MWO model is only applicable for particles with thin double layer, \(\kappa a \gg 1\), and that it fails to predict the behavior at low frequencies (i.e., almost all frequencies below \(f_{\kappa_0}\)) [41,42]. A rigorous approach to obtain
$K_{CM}$ for all double layer thicknesses and frequencies is the numerical solution or simplification of the Poisson–Nernst–Planck (PNP) equations, which describe transport of ions due to electric fields and concentration gradients. This has been summarized in a comprehensive review article by Hui Zhao [42]. For reference, in 0.01 mM KCl, $\sigma_M = 1.5 \, \mu S/cm$, the Debye length $\kappa^{-1}$ is roughly 100 nm; hence, $\kappa a = 0.1$ for a 500 nm particle, corresponding to a thick double layer, and around 40 for a 2 µm particle, corresponding to a thin double layer. In the limit of thin double layer, the numerical polarization coefficient from the PNP equations is equivalent to two models. In the high-frequency regime, the MWO model gives the $K_{CM}$, using Equations (2) and (3). However, without the inclusion of a Stern layer conductance, thus $K_S = K_S^0$. At low frequency, the double layer polarization causes a difference in ionic concentration around the diameter of the particle. Ion diffusion between the bulk and the concentrated regions as well as diffusion along the surface of the particle will effectively reduce the dipole from the one predicted by the MWO model at low frequencies. This is described by the theory of Dukhin and Shilov (termed DS model, see, for example, Grosse and Shilov [43]). In the low-frequency limit, the double layer is in equilibrium; this is associated with the time constant $a^2/D$, with the ion diffusivity $D$. Consequently, when $f$ increases above $D/a^2$, the influence of ion diffusion becomes smaller and vanishes and the MWO model becomes valid. The DS and MWO model are shown in Fig. 1B, red line and equations are given in the Supporting Information, Section S1.

For arbitrary DL thicknesses, the PNP equations must be solved numerically. At moderate and high relative dipole thickness, the electrophoretic motion of the particle itself dominates the polarization behavior. Then, qualitatively, the polarization looks similar to that predicted by the MWO model (pDEP at low frequency and nDEP at high frequency) with a single dispersion (cross-over) at frequencies being between $Dk/\sigma$ and $Dk^{-5}$. Quantitatively, however, the polarization coefficient will differ from the MWO model and the low-frequency polarization coefficient can become significantly $>1$. This is in contrast to the MWO model that uses the Clausius–Mossotti factor, Equation (2), that is by definition between $0.5$ and $1$. The theory has later been extended to incorporate steric effects [44], soft particles [45], and concentrated electrolytes [46]. A more thorough discussion on the polarization behavior can be found in Section S1 of the Supporting Information.

### 2.4 Polarization of metal and semiconducting particles

The polarization behavior of metal particles is summarized in a review by Ramos et al. [47]. The influence of the double layer on the polarization has been ignored for a long time. In this case, a conductive particle in a lossy dielectric was modeled as a perfect conductor. Using Equation (2) and assuming a particle conductivity of around $5 \times 10^7$ S/m (which corresponds very roughly to gold) in de-ionized (DI) water, this yields $\text{Re}[K_{CM}] = 1$ for frequencies up to $5 \times 10^{15}$ Hz, thus far beyond the frequency usually used for DEP. This simplification is only valid for frequencies well above the reciprocal of the double layer charging time. Below that frequency, the DL is fully charged, and the field lines surround the particles. The situation is equal to that of an insulating particle and $\text{Re}[K_{CM}]$ for a sphere would be $0.5$. In this case, the charges induced in the metal are screened by the ions in the electrolyte that form the DL; consequently, the electric current is tangential to the particle surface. Incorporating this, the real part of the Clausius-Mossotti factor for a metal particle is given by [48]

$$\text{Re}[K_{CM}] = \frac{\Omega^2 - 2}{\Omega^2 + 4}.$$  

Here, $\Omega = \omega C_{DL}/a/\sigma_M$ is the dimensionless frequency, normalized by the double-layer charging time. $C_{DL} = \varepsilon_M \kappa$ is the double layer capacitance (per unit area) using the Debye–Hückel approximation. This yields negative DEP up to a frequency of $f_{KO} = \frac{1}{\kappa a} \approx f_{CM}$ and positive DEP for frequencies above (Fig 1B, green line). Note that $\kappa$ and thus $C_{DL}$ scale with $\sqrt{\sigma_M}$, thus $f_{KO}$ also scales with $\sqrt{\sigma_M}$. Consequently, $f_{KO}$ increases with medium conductivity. Assuming a 0.01 mM KCl solution ($\sigma_M = 1.5 \, \mu S/cm$) results in a $C_{DL}$ of 0.0072 F/m$^2$ and a calculated $f_{KO}$ of $\approx 3$ kHz. In reality, surface roughness and surface charges increase $C_{DL}$, resulting in lower $f_{KO}$; for example, García-Sánchez et al. extracted values for $C_{DL}$ between 0.16 and 0.18 F/m$^2$ for gold-coated polystyrene particles of 10–45 µm diameter [48]. In Fig. 1B, we assumed $C_{DL} = 0.1$ F/m$^2$. Observing the motion of conducting particles in non-homogeneous fields, in theory one also needs to consider the induced-charged electrophoretic (ICEP) motion of particles. The full effect of DEP and ICEP is termed Dipolophoresis [49,50]. However, this has not been observed experimentally, since ICEP is usually much smaller than predicted for a variety of reasons (e.g., surface roughness and electrochemical reactions) and the DEP behavior dominates the ac translational motion of conducting microparticles [48,51].

Considering semi-conducting particles, the same low-frequency behavior can be observed. Then, particles show two dispersions [51,52]: A low-frequency dispersion from the EDL charging (according to Eq. (4)) and a high-frequency dispersion from the Maxwell–Wagner polarization (since $\sigma_F$ of semi-conducting particles is only around 0.1 S/m instead of $5 \times 10^7$ S/m as in the case of fully conductive particles). The full Clausius–Mossotti factor then takes a lengthy form and is given in Ref. [51].

### 2.5 Devices for dielectrophoretic separation

DEP separators can separate particles from a liquid (which is termed “enrichment” in this review) or separate one or more target particles from a mixture of suspended particles (termed “classification”). Apart from the former two, this review addresses also other applications of dielectrophoresis, for example, separation including other phases, or
applications apart from separation (Section 3). Nevertheless, we limit the general discussion of device design to particle separation in liquids as this is by far the most common application.

DEP enrichment requires that the DEP force (Eq. (1)) overcomes other acting forces, such as Brownian motion (nanoparticles), drag (in flow operation), or gravity. DEP classification is possible when the DEP force is sufficiently different between two or more types of particles, which requires sufficient differences in either $\Re(K_{CM})$ or particle volume, $a'$. Ideally, $\Re(K_{CM})$ has a different sign which would cause particles to move into different directions but separation is also possible by adjusting the device design and operation scheme to exploit small differences in either $\Re(K_{CM})$ or $a'$. Classification could be either done by selective capture of target particles in field maxima (or sometimes minima) or by deflecting particles with different properties into different outlets in the separator.

Most contemporary DEP separators are microfluidic and based on two principles: either microelectrodes generate an inhomogeneous field (electrode-based DEP) [53,54] or field hurdles distort a homogeneous field generated by electrodes far away from the separation region (electrodeless DEP) [55–57]. Such separators seldom exceed throughputs of 1 mL/h. The most common electrode-based design is a planar array of interdigitated electrodes placed at the channel bottom. In such an array, the electric field maxima are usually found at the electrode edges and the field gradient decreases with increasing perpendicular distance. This design can be used for example for (selective) trapping of particles [58–60] or to deflect particles into different outlets [61,62]. An example is the castellated electrode arrangement (Fig. 2A and B).

Figure 2. Sketch (A) and photograph (B) of yeast trapping in castellated electrodes. Particles experiencing pDEP (live yeast) will form pearl chains stretching across the electrode gap, nDEP particles (dead yeast) form triangular pattern in the gap region. The trapping force on nDEP particles is significantly lower, allowing them to be washed out of the channel. (C) Generic iDEP device with an array of insulating posts. Local field maxima are found in the vertical gaps between the posts (D) so that particles experiencing nDEP cannot pass the individual post lines and are immobilized in trapping bands (E). Sketch (F, G) of particle trapping with positive DEP (red particles) and negative DEP (blue particles) in beads–based DEP filter. In such a design, field maxima (pDEP trapping) are found at the contact points of the glass beads, whereas field minima (nDEP trapping) are found in the empty space (H). (B) Reprinted with permission from Ref. [60], copyright (1994) Elsevier. (C, D) Reproduced from Ref. [92], copyright (2009) with permission of The Royal Chemical Society. (E) Reprinted with permission from Ref. [64], copyright (2020) Springer-Verlag GmbH. (H) Reprinted with permission from [83], copyright (2007) John Wiley and Sons.
Electrodeless separators can feature a variety of designs. Hurdles are usually fabricated from an isolating material, which is commonly referred to as insulator-based DEP (iDEP). The most common design appears to be an array of insulating posts (Fig. 2C) in which the electrodes are placed at the inlet and outlet of the chip [63–67]. The electric field will be disturbed at the posts generating local field maxima in the vertical distances between the posts (Fig. 2D). In traditional operation modes, particles experiencing negative DEP are repelled from these field maxima forming so-called trapping bands in front of each line of posts (Fig. 2E). Other designs feature one [68] or several constrictions [69,70] or classify particles due to deflection into different outlets [71,72].

Electrode-based separators usually operate at low voltages (around 10 V) and high frequencies to exploit differences in the first cross-over frequency of cells (Fig. 1B, blue line). Electrodeless or iDEP separators instead usually require higher voltages (around 1000 V) and operate at dc or low-frequency ac to exploit differences in electrophoretic properties and low-frequency polarization behavior. Specific application areas and the strengths and drawbacks of both types are discussed in Section 3.3 of the Supporting Information.

Separation of particles at industrial production scale, in material recycling, or in the mining industry requires devices operating at substantially higher throughput than the previously presented microfluidic devices. While the early works showed very high throughput (as microfluidics was not yet common), DEP application beyond the analytical scale is nowadays seldom.

It is important to note that the interpretation of “high” in “high throughput” depends on the concentration of the input particle mixture, the target particle percentage, their perceived value, and the throughput achievable with existing technologies. As an example, due to the high value of pure metallic carbon nanotubes (ca. 500–1000 USD per mg), separation of metallic from semiconducting carbon nanotubes is economically feasible at throughputs substantially lower than 1 g/h. Assuming a gold content in low-grade ore of 1–4 g/gold per ton of ore and a price of approximately 45 USD per gram gold, it is obvious that extraction of gold from low-grade ore only becomes feasible at several orders of magnitude larger throughputs. Further, the absolute solid content in combination with the volumetric flow rate defines the throughput. As discussed in Section 2.1, when separating particles experiencing pDEP and nDEP from each other, an increasing solid content will cause decreasing separation efficiency due to particle–particle interaction.

Similar to microfluidic DEP separators, high-throughput DEP devices also have two main designs: counter electrodes and DEP filtration. A classic example of a DEP device with counter electrodes is the macroscopic cylindrical concentric setup employed by Pohl and co-workers. The inner electrode was either an insulated or bare wire and the outer electrode was a glass tube either coated with graphene or with a spiraling wire wrapped on the inside. In such a setup, the electric field is maximum at the inner electrode and decreases towards the outer electrode. Then, pDEP particles accumulate at the inner electrode and nDEP particles at the outer electrode. Using non-conductive solvents, Pohl showed the enrichment or depletion of polar (polyvinyl chloride) or non-polar (polyethylene) particles due to either pDEP or nDEP, respectively [73–75] (see Section 3.1). In continuous operation, a particle suspension is fed from the top with particles randomly distributed on the entire fluidic cross-section. Liquid samples are extracted at two outlets, one close to the inner and the other close to the outer electrode.

In 2008, our group followed a similar route for gold particle separation [22], with the major difference of using aqueous suspensions. Here, the electrodes were a metal wire and plate at 6 mm distance. In such a configuration, pDEP particles are attracted by the wire whereas nDEP particles move toward the plate. We successfully classified macroscopic gold particles in DI water from heavy minerals and observed accumulation of gold particles at the wire, thus underlining the DEP effect.

In a series of papers, Sano, Tamon, and co-workers developed and applied a mesh-stacked DEP separator that was operated batch-wise. It was, according to the authors, suitable for large-scale separation [14,76–79]. This consisted of multiple aligned sheets of stainless-steel wire meshes (aperture 0.5 mm, wire diameter 0.29 mm). A voltage of up to 200 Vpp (= peak-to-peak voltage) was applied across adjacent sheets. A DEP force is then generated between two sheets, dragging pDEP particles to the surface of the wire mesh whereas nDEP particles accumulate in the center region between meshes. To achieve separation, the wire mesh is submerged into a solution containing the target particle mixture and the voltage is turned on. In a second step, the mesh stack is transferred to a second reservoir containing only liquid and the voltage is turned off to release the trapped particles.

A very promising approach for the high-throughput DEP separation, and to the best of our knowledge, the only approach being able to work with aqueous suspensions, is dielectrophoretic filtration, which is discussed in detail in Section 3.6. Briefly, DEP filtration operates on a similar premise as insulator-based DEP: an originally homogeneous field is disturbed at the interface of a macroscopic dielectric porous medium. The DEP effect does not depend on the asymmetry of the electrodes but on the local field gradient induced at the surface of the solid-liquid surface of the porous medium. Ideally, the pore size is much larger than the target particle size so that separation is (almost) independent of mechanical filtration and dominated by the DEP force. The macroscopic porous medium can be monolithic or a packed bed and is either sandwiched between two electrodes [80–85] or arranged between two [86–88] or more [89] concentric electrodes. Electric field maxima are on the surface of the pores or at contact points of the packing material forming the porous medium (Fig. 2F–H). Due to the structure’s irregularity, a virtually infinite amount of electric field maxima is created that can be used for (selective) particle capture. Similarly to iDEP, this design allows decoupling electrode distance from field gradient magnitude (as the field gradient is determined by the geometry of the porous medium). The
advantage over iDEP is the easier scalability as it does not rely on microfluidic fabrication techniques.

DEP filtration can be used with glass beads or polymer and copper meshes as extensively used in the separation of non-conducting particles from oil at high throughput [86–91]. In our group, we used a monolithic polymer foam of 20 to 160 µm pore size as a filtration matrix to separate very small particles (340 nm) from highly conducting aqueous medium [82]. DEP filtration is also employed in biomedical applications [83–85], for example for the selective enrichment of live yeast cells from a mixture of live and dead cells at high throughput [84].

3 Applications

Thanks to its high selectivity and controllability, DEP is applied in particle (solid and liquid) enrichment and classification as well as intensification of conventional separation technologies such as demulsification and membrane filtration. DEP was also used for assembly of nanostructures, which has already been elaborately reviewed [93–96] and therefore will not be discussed here. A summary of all discussed applications can be found in the Supporting Information, Table S4.

3.1 The beginnings

To the best of our knowledge, the first reported application of dielectrophoresis was by Hatfield in the 1920s for the separation of minerals [1]. In his 1996 review [97], Andres nicely summarizes and discusses Hatfield’s separator and gives an overview of the state of dielectric separation of minerals until the end of the last century. Briefly, Hatfield used 50 Hz ac electric fields to separate minerals based on their apparent permittivity. The theory for frequency-dependent polarization effects was not well established at that time. Thus, Hatfield tabulated complex values of the permittivity that included the charge contribution but were only valid at one specific frequency. Therefore, changing the suspension’s conductivity or the applied field frequency was left untouched in his experiments. Hatfield investigated the separation of a wide variety of minerals and ores. He used mixtures of nitrobenzene ($\varepsilon_r = 36.4$) and kerosene or xylol ($\varepsilon_r = 2$) as suspension that had a low conductivity and gave the possibility to separate a wide range of materials. Hatfield devised several batch separators in his patent [98] with different electrode configurations. For example, he invented an electrical sieve with screen-type electrodes that attracted high-permittivity minerals while low-permittivity materials just fell through (Fig. 3A and B). In the 1920s, a separation plant with a throughput of 1 ton/day was working in Cornwall (England) to separate tin and vanadium ores. The work was later discontinued due to the suspension medium’s toxicity [97].

It was not until three decades later that Pohl coined the term “Dielectrophoresis” and described its mechanism. He experimentally succeeded in applying the theory for the separation of carbon black from polyvinyl chloride in di-isopropyl ketone using a batch precipitator [2]. Later, Pohl designed a continuous DEP separator using a foil-lined Pyrex Tube of...
20 mm inner diameter and a Teflon-coated metal wire as inner electrode [73] (Fig. 3C). Applying 4 kV at 60 Hz, he continuously extracted streams at the outlet and tested in two separate experiments different material combinations: First, the polar material PVC (\( \varepsilon_r = 4.6 \) at 100 Hz) suspended in a non-polar suspension (1:1 v/v mixture of CCl\(_4\) and benzene, \( \varepsilon_r = 2.2 \) at 100 Hz), and second, the nonpolar polymer, polyethylene, suspended in a polar medium (6:4 v/v mixture of acetonitrile and nitrobenzene). PVC presented pDEP and accumulated at the inner electrode while polyethylene showed nDEP and accumulated at the outer electrode. Pohl and Schwar investigated the influence of operation and device parameters, such as the electrode dimensions, voltage, different currents (dc or ac), electrode insulation, and particle size, on separation efficiency [75]. Later, Pohl and Plymale showed separation of PVC from a liquid medium with two continuous DEP separators using different electrode configurations: cylindrical electrodes with pumped suspension at 750 mL/h flow rate and isomotive electrodes using gravity-assisted separation [74]. They also showed different particle species from each other, such as sodium dichromate from TiO\(_2\), rutile from PVC, SiC from Al\(_2\)O\(_3\), SiC from SiO\(_2\), SiC from CaF, and zirconia from rutile [74]. Nearly all studies used DEP to separate large technical particles (over 50 µm) in organic liquid media with low-frequency electric fields (dc or \( f < 100 \text{ Hz} \)).

### 3.2 Solid–liquid separation

This section lists studies addressing the separation of solid particles suspended in a liquid medium. The first section addresses non-selective separation (enrichment) while the second section addresses material-selective separation (classification). We note that many experimental studies use polystyrene as model particles, although devices or theories are later aimed at biological applications. We do not discuss such studies here and refer to the review of Chen and Yuan [38].

#### 3.2.1 Enrichment

A very important technical application in the non-selective separation of particles from the liquid medium is the filtration of catalyst contaminants from oil (the Gulftronic separator by Fritsche and coworkers and follow-up studies), which is thoroughly discussed in Section 3.6 and omitted here.

Dielectrophoresis has been used for the trapping and separation of nanoparticles [99–101]. For example, Barik et al. [101] used atomic layer lithography to create nanogap electrodes with 9 nm electrode distance (Fig. 4A and B). Since \( \nabla |E|^2 \) roughly scales with electrode distance to the power of \(-3\), such small electrode distances allow effective capture of nanoparticles at extremely low voltages (below 1 V). This avoids unwanted Joule heating, bubble formation, and electrochemical reactions. They demonstrated the capture of 30 nm PS particles, 8 nm CdSe quantum dots, and 40 nm nanodiamonds at 200–700 mV voltage and 100 kHz–1 MHz frequency. They further calculated the relation between applied voltage and minimum distance from the gap required to overcome Brownian motion for different particle sizes (Fig. 4C). Midelet et al. [100] experimentally captured 80–150 nm gold particles using indium tin oxide microelectrodes (distance ca. 20 µm) at 5 V\(_{pp}\) and without flow. One of their findings is that Brownian motion helps to transport particles close to the electrodes and that the investigated nanoparticles showed anomalous polarizabilities much larger than predicted from the Clausius-Mossotti factor (i.e., a calculated Re[K\(_{CM}\)] larger than 1), which they attribute to the large double layer influence. This matches the predictions from the PNP equations that yield K\(_{CM}\)-values much larger than 1 for particles with a thick double layer (Section 2.3).

Calero et al. [102] recently presented an electrokinetic-biased Deterministic Lateral Displacement channel (using isolating posts) that allowed the size separation of submicron particles (100, 500, and 1000 nm). The device operates using either ac, dc, or a combination of both in order to exploit size, polarizability, and \( \zeta \)-potential differences between particles. A device by Beech et al. [103] uses similar principles but with metal-coated posts.

Batton et al. [104] investigated the removal of heavy metal ions from wastewater in a laboratory-scale DEP system with castellated microelectrodes. An adsorbent, hydroxyapatite (HAP), adsorbed heavy metal ions in water and DEP was used to trap HAP particles after adsorption. The concept’s success gives a hint of DEP’s potential in wastewater treatment. Adekanmbi et al. [105] studied the feasibility of quantifying the amount of adsorbed rare earth element (REE) ions on a biosorbent by DEP. Biosorption has been discussed as a cost-effective environmentally friendly biological alternative to classic REE recovery methods. The amount of REE adsorbed on the biosorbent influences the frequency-dependent DEP behavior allowing a DEP-based quantification.

#### 3.2.2 Classification

Separation of micron or submicron metal particles from metal oxides or plastics is important for example in the processing of low-grade mineral ores or in the recovery of precious metals from scrap. This especially holds when target particles are small or only available at low concentration. Then, traditional separation methods either fail, are economically unfeasible, or, in the case of leaching, linked to personal and environmental hazards.

Lungu [106] presented a batch method to separate dry silver and gold particles from mineral waste (dielectric particles) at ppm-level concentrations by applying a uniform ac electric field. The field gradient is induced by the dielectric mineral waste particles in the mixture. He could enrich submillimeter metal particles at the surface of the mixture by a factor of 19 after 10 runs at 4 kV/cm field strength. It was
considered a promising technique to be applied at industrial scale.

A prototype to bridge the scales between microchannels and industrial requirements was developed by Du et al. [22] for separating native gold particles from original primary gold ore in an aqueous medium. The separator used a wire-plate configuration with a Y-separator outlet and a large electrode distance of 6 mm. Applying an ac voltage of 190 V$_{rms}$ ($\approx$ root mean square voltage) at 200 kHz, they achieved a separation efficiency of 88% at high throughput (2.4 mL/s). However, the Joule heating induced by the high electric field (32 kV/m) disturbed the particles’ DEP motion and hence reduced the separation efficiency.

Separation of micron-sized gold particles from polystyrene in microfluidics has also been shown [107,108]. Due to the throughput limitations, such studies are interesting rather than from an academic perspective. For example, Weirauch et al. [108] used a microfluidic iDEP channel employing an array of insulating posts. Using dc voltages, they separated 2.4 and 4.5 µm gold-coated PS particles from pristine PS particles of equal size. A high voltage trapped both particles (Fig. 4E). A subsequent stepwise voltage decrease caused the plastic and gold particles to be released individually (Fig. 4F and G).

Ballantyne et al. [109,110] qualitatively examined DEP effects for different minerals, such as galena, quartz, pyrite, and others in distilled water. Almost all minerals presented obvious positive or negative DEP effect, proving the feasibility of DEP application in mineral separation. To quantify the DEP force on minerals suspended in ethanol, they developed a simple but effective apparatus on the deflection of the particle attached to a glass fiber [109]. They examined size and material influence [110] and concluded from their experiments that DEP could be applied in mineral processing such as pretreatment of gangue, recovery of ultra-fine particles, and assay of minerals in laboratories.

Using a stacked stainless-steel separator (see Section 2.5), Sano et al. [14] separated tungsten carbide from diatomite suspended in ethanol. Tungsten carbide particles presented pDEP and got attracted by the mesh electrodes while diatomite particles showed only a weak DEP effect. They applied 100 V$_{pp}$ at frequencies between 50 and 800 kHz. To
achieve significant tungsten carbide enrichment, a multi-stage operation was proposed and 3–15 required steps were theoretically predicted depending on the desired enrichment factor (between 10 and 20). Such a design could be easily scaled up for high throughput by increasing the numbers of stacked meshes and separation stages.

In a proof-of-principle study, using interdigitated micro-electrodes, Chen et al. [15] demonstrated the potential of DEP to separate different rare earth oxides (REO) depending on their valences: They found that depending on frequency, REO with different metal valences require a different minimum voltage to be moved by DEP that indicates different $K_{CM}$ values.

To decrease the addressable particle size and bridge the scales between micrometer and nanometer, Sano et al. [76,77] used carbon nanotubes (CNT) that act as nanoelectrodes and enhance the local $\nabla|E|^2$. The concept was theoretically discussed for the separation of nanometer particles by size [77] and experimentally demonstrated [76] for the separation of 10–20 nm TiO$_2$ (experiencing pDEP) from SiO$_2$ (experiencing nDEP) in ethanol. CNTs with 10–20 nm diameter (thus of the same size as target particles) were directly synthesized on two flat stainless-steel electrodes at 3 mm distance (Fig. 4G). The device operated at 1 mL/min throughput and an applied voltage of 1000 V$_{dc}$. Starting from an initial weight ratio of TiO$_2$/SiO$_2$ of 1, the weight ratio of the trapped TiO$_2$ particles increased to 10.6. Sano et al. [79] also synthesized CNTs on their stacked stainless-steel mesh separator to purify titanate nanotubes from TiO$_2$ impurities left from the synthetization procedure in aqueous suspension. Zhao and Li [111] used a nano-orifice in a PDMS chip to generate large local $\nabla|E|^2$. With their design, they could deflect continuously flowing 140 nm PS particles and 150 nm magnetic particles (Fe$_3$O$_4$ core) into different outlets at high efficiency.

The separation of carbon nanotubes (CNT) into conducting and semi-conducting fractions is a well-suited application for traditional microfluidic DEP separators: CNTs are of sufficiently high value that even the purification of small volumes is economically feasible. In a seminal paper, Krupke et al. [112] demonstrated separability of single-walled CNT on the droplet scale. They also found that the interaction of the CNTs and surfactant present in the aqueous suspension induces a different surface conductance on metallic and semiconducting CNTs [113]. This results in a different frequency-dependent DEP response of metallic and semiconducting CNTs. At low medium conductivity, both semi-conducting and conducting CNTs show pDEP. At high medium conductivity ($\sigma_m > 3 \times 10^{-7}$ S/m), semiconducting CNTs show nDEP in the upper kHz and MHz frequency range. Later, Kang et al. [114] also reported the ratio of CNT conductivity to medium conductivity (controlled by choice of surfactant) to be key for separation of semiconducting from metallic CNTs. Kang et al. [115] and Shin et al. [62] used microfluidic channels with interdigitated electrodes to continuously separate metallic and semiconducting CNTs at high efficiency and flow rates in the µL/min range (Fig. 4H).

### 3.3 Liquid/Liquid separation

Due to differences in size or material properties, DEP can be used to sort emulsion droplets. A precise control of the droplet size is beneficial for high-quality emulsion processes. Many drugs, food products, or synthetic materials consist of emulsions and many industrial fields rely on emulsification processes. Dielectrophoresis can be used to achieve a narrow size distribution of such emulsion droplets (as the force scales with the droplet’s volume, Eq. 1). Further, during emulsification, much smaller satellite droplets are generated along with the master droplets. They are undesirable and need to be removed. Hung et al. [116] demonstrated the possibility to sort oil-in-water droplets using optically induced dielectrophoresis operated in batch mode. Applying 60 V$_{pp}$ at 100 kHz, they successfully sorted droplets with sizes from 2–40 μm with a resolution of approx. 2.5 μm. Sun et al. [117] employed a device that is based on a combination of ac DEP and ac electrothermal fluid flow to separate 50 μm master droplets from satellite droplets at a flow rate of 1.8 μL/min. Satellite droplets were approximately one order of magnitude smaller. They employed different voltages between 10 and 20 V at a frequency of 1 MHz. Sorting droplets based on material or composition is important in the wide field of droplet microfluidics. For example, this can be used for high-throughput screening of droplet-based microreactors (i.e., one droplet is an entire reactor). Ahn et al. [118] developed a high-speed microfluidic sorter capable of sorting arbitrary water-in-oil droplets at a speed of 1.6 kHz. The device, however, was not intrinsically selective. Instead, a pulsed DEP force employed on demand would sort target particles into different outlets (depending on which electrodes were energized). Such a system can only be used for selective separation in combination with a property-selective droplet detection system, for example via image capturing. Zhao and Li [119] employed an electrode-based microfluidic chip to continuously sort ionic liquid and silicone oil droplets in water according to their material. The droplets were around 15 μm in size and could be directed into different outlets depending on their concentration upon application of voltages between 10 and 20 V$_{pp}$ and frequencies above 100 kHz. The same group also devised a chip for the separation of Janus droplets from silicone oil droplets in water using wall-induced DEP [120]. Janus droplets are droplets where one side is coated with a conducting material, thus both hemispheres of the droplet have different properties. They have a variety of emerging applications, for example as self-propelling micromotors or for programmable drug delivery. By applying dc voltages between 125 and 375 V/cm across a 1-mm-long channel, the authors separated 25, 55, and 75 μm Janus and oil droplets by size, and Janus and oil droplets of equal size from each other.

### 3.4 Electrocoalescence

Electrocoalescence is the process of separating emulsions by electric fields. Demulsification is important for many
chemical processes, with a prime example being the removal of dispersed water from crude oil before refining. Different methodologies exist to break up emulsions. Examples are chemical demulsification, membrane demulsification, employing surfactants, or changing parameters that influence the emulsion stability, such as temperature or pH-value. Electrocoalescence is considered advantageous from an economic and ecologic point of view compared to other methods [121]. It has been used in the petroleum industry for over a century. The applied technologies and theoretical understanding have been discussed in two reviews by Eow et al. [122,123]. The most commonly employed setup is a coaxial electrode configuration and both ac, dc, and pulsed dc fields have been applied. Among other factors, electrocoalescence occurs because of the interaction of the induced dipoles in two droplets causing an electrostatic attraction between the droplets [124,125]. The mechanism is a manifestation of dielectrophoresis, and the underlying physical principle is identical to particle-particle interaction in DEP (see, e.g., section 4.6 in Ref. [17]). Briefly, the induced dipole in a droplet causes a locally inhomogeneous field giving rise to a net pDEP motion in a second polarized droplet. Electrocoalescence is usually employed for water-in-oil droplets because it allows the application of high electric field strengths. Applying strong electric fields to coalesce oil-in-water droplets causes water electrolysis and contamination of the suspension. Nevertheless, demulsification of oil-in-water droplets has been reported at low [126] and high electric field strengths [127]. Mhatre et al. [128] investigated the influence of the electric field configuration for coalescence of water-in-oil and oil-in-oil droplets. They found for a conductive and thus polarizable dispersed phase (i.e., water-in-oil droplet) the application of a non-homogeneous field to increase coalescence rate. This was attributed to a beneficial DEP motion of droplets and electrohydrodynamic flows. They also found that for a less polarizable dispersed phase (i.e., oil-in-oil droplet), larger and more homogeneously distributed field gradients are required to achieve efficient droplet coalescence (as they experience less net motion due to lower polarizability). A somewhat more recent view on the topic can be found in the review of Zolfaghari et al. [121].

3.5 Fouling suppression in membrane filtration

Fouling is a problem occurring in membrane filtration processes. With increasing operation time of a filter, organic and inorganic particles as well as biomass accumulate on the filter surface and inside the pores and decrease the effective filter permeability (that is, the volume flow achieved at a certain pressure difference). Fouling decreases the membrane lifetime and causes increasing operational costs over time due to reduced effluent and increased pressure requirements. Fouling could be suppressed by different methods, for example, shear forces induced by vertically rising bubbles (aeration), chemical cleaning, backwashing, or ultrasound. All of those methods suffer from individual drawbacks. Most bioparticles as well as non-conducting particles above 1 µm in size show negative DEP at medium conductivities of drinking water and above (» 1 mS/m) and certain frequencies. This suggests the introduction of a DEP force pointing away from the membranes to keep particles from attaching to the membrane.

The principle was first proposed by Molla and Bhattacharjee [129] and experimentally validated using interdigitated electrodes on a glass slide [130]. The first integration of dielectrophoresis into a membrane module was done in our group. We investigated different electrode configurations, such as asymmetric electrodes placed on both sides of the membrane in a cross-flow module [131] and macroscopic cylindrical interdigitated electrodes (IDE) placed under the membrane module in cross-flow [132] and membrane bioreactor application [133]. We further introduced field obstacles between the electrodes in cylindrical IDE [134] and directly screen printed microscopic IDE on top of the membrane [135]. A design with cylindrical IDE mounted below the membrane module (0.6 mm diameter with 1 mm edge-to-edge distance) is shown in Fig. 5. Application of 200 Vrms could increase the service time, i.e., time until flux decreased to 69% of the initial value, by a factor of 9 for the filtration of a 5 g/L clay suspension [132]. To reduce the energy demand, we introduced either floating electrodes (i.e., non-excited metal electrodes) or insulators (i.e., of the same shape as the electrodes but of insulating material) in between the excited electrodes in the cylindrical IDE array. We applied this concept to a submerged membrane bioreactor (MBR) module with 2 mm diameter of floating electrodes, excited electrodes and insulators and 2 mm edge-to-edge distance between them. We achieved a five times higher membrane service time, taking a decrease to 55% of the initial value as reference, by applying 50 Vrms at 50 Hz for the filtration of 5 g/L biomass [134]. Applying this concept continuously for conductive wastewater, however, would result in a high energy demand and substantial Joule heating causing rapidly increasing temperatures, which might damage the membrane. Consequently, application in MBR system was quite restricted [136].

To solve this problem, we proposed, designed, and tested the concept of screen-printing microscopic IDE directly on the membrane. The IDE have a width of 75 µm and an edge-to-edge distance of 300 µm. This allows the generation of sufficiently high DEP forces using voltages as low as 10 Vpp. A submerged membrane bioreactor pilot plant with 10 DEP-functionalized membrane modules was operated to filter water from an advanced treatment pond from a municipal wastewater treatment plant in Osterholz-Scharmbeck (Germany). The DEP modules have been compared to non-functionalized conventional modules for a duration of several months and could provide about 1.5 times higher permeate flux upon application of 12 Vpp at 100 kHz [135].

Alternatively, it is possible to employ the concept of insulator-based DEP to suppress fouling of nanoporous membranes. Using molecularly thin membranes (10–100 nm) with pores of 5–100 nm diameter, it is possible to induce a field gradient at the pore edges by applying an electric field across the membrane. Similar to iDEP...
designs relying on constrictions, this causes a field maximum at the pore edge that increases with increasing edge sharpness and decreasing pore size. This field gradient itself can be strong enough in order to mitigate fouling of nanoparticles or molecules in the pores. This effect has been numerically investigated by Mukaibo et al. [137] and Ren et al. [138].

3.6 DEP Filtration

To the best of our knowledge, DEP filtration is the only scalable technique capable of material-selective separation (i.e., classification) of nano and microparticles in aqueous suspensions at high throughput (i.e., at least mL/min). Because of this, we dedicated a section to studies researching or applying DEP filtration for industrial or technical application. Most of these studies would also fit in Section 3.2 but have been omitted there for brevity.

Analogous to the early work in DEP applications, first applications of DEP filtration were for the separation of particles in organic liquid media such as oil. Glass beads as filtration media were widely used in the early DEP filtration processes because the membrane separation technique was not considered to be of industrial importance in the mid-1970s. The first DEP filter was invented by Fritsche and coworkers [90,139,140] and was commercialized in 1977 as Gulftronic separator (Fig. 6A). It employed glass beads as filtration matrix and was used for a variety of applications. Examples are separation of fluid catalytic cracking (FCC) catalyst fines from decanted oil, removal of metallic fines from metalworking fluids, for example in foil rolling, separation of hydrogenation catalyst particles from vegetable oil [141,142]. When purifying FCC oils, a concentric separator with 10 cm inner diameter achieved a removal efficiency of up to 99 wt% to solid contents less than 5 ppm upon application of 30 kV dc [139]. In the beginning of the 1980s, DEP filtration and especially the Gulftronic separator were extensively discussed by Lin and Benguigui [141,142]. The authors also give a very comprehensive list of possible applications, such as removal of impurities from oil, enrichment of precious metals, separation of metal from dust in material recycling, or the dielectric separation of minerals. They later performed own experiments in non-conductive suspensions. Using a concentric separator of 5 cm diameter filled with 6 mm glass beads and flow rates of approximately 1 L/min, they achieved high separation efficiencies of 50–60% for different particles, i.e., MgO, Cu, Ilmenite and PVC. Particle sizes were between 70 and 100 µm and dc voltages as high as 10 kV [87]. They later also discussed the influence of ac frequency and suspension conductivity on the separation [86,88]. Later, Li, Guo, and co-workers studied experimentally and numerically the DEP filtration of catalyst particles from oil [143–146].

A similar concept, although with several concentric metal shells, was used by Wakeman and Butt. They investigated the separation of PVC (mean 28.3 µm) and air conditioning test dust (1–100 µm, mean 10 µm, median 5.2 µm) from Tellus 37 oil as well as demulsification using a DEP filtration process with 500 µm glass beads [89]. The throughput was up to 180 L/h and the separation efficiency between 0 and 60%. It increased with field strength (investigated voltages from 6–12 kV dc), decreased with superficial velocity, and decreased with observed particle size fraction. The authors argued that the filter could be easily cleaned by switching off the field and had only very low energy demands. It could have potential applications when a multipass filter is acceptable. A similar concept was employed by Sisson et al. for the filtration of 50 nm and 300 nm silica particles from tert-amyl alcohol [147]. Shen et al. employed a different concept of sandwiching several layers of polypropylene mesh (wire diameter and opening 100 µm) between two oppositely excited copper meshes (wire diameter 114 µm, opening 152 µm) which are then wound several times around a core tube with openings in the wall [91]. This very simple, low-cost fabrication method
is easily scalable since the required materials are easily available and handleable. The authors envisioned an application for the separation of contaminations from engine oil when neither high-pressure drops nor large applied voltages are allowed.

All DEP filtration applications above were focused on the filtration of particles from oil in inhomogeneous electric fields. We want to highlight that DEP filtration is not limited to applications in the oil industry. When using aqueous suspensions, DEP filtration finds application in a variety of fields. For the first time, our research group experimentally proved the principle with a case study: DEP filtration was applied for the recovery of 340 nm layer-by-layer–produced particles from highly conductive aqueous media with low energy demand [82]. We used a monolithic polymer foam with 20–160 µm pore size as filtration matrix sandwiched between two metal plates and achieved throughputs of 1 mL/min at 200 V_{rms} voltage at 200 kHz. Using these parameters, we achieved a maximum separation efficiency of 38% in our lab-scale DEP filtration process. Based on theoretical and experimental investigation, we proposed design rules for DEP filtration usable for both technical and biological particle separation in aqueous media at high throughput [80]. We further employed monolithic mullite foams with median pore window diameters from 180 to 270 µm (Fig. 6B and D), and demonstrated that DEP filtration can effectively separate polystyrene and graphite particles of different sizes (0.5, 3, and 4.5 µm) from aqueous medium at high volumetric flow rates from 1 to 9 mL/min [81]. Applying 600 V_{rms} at 15 kHz, we achieved separation efficiencies between 60 and 100% depending on throughput for 500 nm polystyrene particles. We could further demonstrate that the application of monolithic foams is beneficial compared to glass beads that we attribute to the existence of sharp edges at the pore windows. We discuss the possibility of material-dependent separation by finding a suspension conductivity at which polystyrene is almost non-polarizable at the chosen frequency. This could allow a material-selective filtration of graphite (Fig. 6C). Further, we could resuspend 92% of formerly trapped particles by increasing the flow rate and turning off the electric field [81].

### 3.7 Solid–air separation

#### 3.7.1 Enrichment

The application of dielectrophoresis to trap airborne particles is highly interesting for the cleaning of air, especially to separate airborne particles smaller than 1 µm in size. This is important as they pose both environmental and health hazards. Conventionally, separation is done for example using filters, which require constant replacement, or electrostatic precipitators, which require particles to be charged. Alternatively, dielectrophoresis can be employed for charge-independent low-maintenance prefiltering. The DEP force depends linearly on the medium permittivity (Eq. (1)) and due to the low permittivity of air, \( \varepsilon_m \approx 1 \), the DEP force on an airborne particle is almost two orders of magnitude smaller compared to particles suspended in water. In principle all particles should show positive DEP in air because of the low permittivity of air. However, the absence of the electrostatic double layer that would form in aqueous suspensions causes particles with low \( \sigma_p \) and \( \varepsilon_p \) to only show a weak pDEP effect (which could be increased by increasing humidity [148]). DEP filtration of airborne particles has been researched end of the 1970s by
the Lawrence Livermore National Laboratory (LLL) in the US for the prefiltering in nuclear ventilation systems [149]. They sandwiched conventional HEPA filters between two stainless steel plates spaced 13 mm apart. Upon application of electric fields as high as 1.2 MV/m, the fibers polarized which caused local field inhomogeneities and thus attraction of airborne particles. At flow velocities between 0.16 and 0.65 m/s, they observed filtration of airborne 0.95 µm sodium chloride particles at efficiencies of 99%. The research on DEP filters was later discontinued as the team of the LLL concluded that the DEP effect is negligible for small particles [150].

Later, it was shown that DEP is in fact capable of separating small airborne particles [151,152]. Lungu et al. [152] demonstrated separation of airborne nanoparticles (with sizes from 40 nm to 380 nm) from flue gas in interdigitated electrode arrays having width and spacing of 100 µm. Using a numerical analysis that was qualitatively verified by experiments, they showed that the particle concentration in the gas stream decreases with increasing number of electrodes they pass. This is due to a pDEP attraction of the gas particles by the interdigitated electrode array. Operating conditions were between 12 and 36 V at 50 Hz.

3.7.2 Classification

Dielectrophoresis has been used to separate airborne fibers according to their length. Various fibers are associated with lung diseases such as asbestosis and lung cancer and the fiber toxicity is determined by their length. To perform studies investigating the influence of fiber shape on toxicity, researchers require monodisperse length fibers. Separation of airborne fibers according to length was not possible using established classifiers. This motivated Baron et al. [153] to develop a fiber length classifier based on dielectrophoresis. It consisted of two concentric steel cylinders forming an annular duct of 3.18 mm (Fig. 7A). A high-voltage ac field is applied across the duct which causes fiber migration towards the inner electrode because of the dielectrophoretic force. The inner electrode was coated with oil causing fibers to stick upon impact. A sheath flow is directed through the gap and the inlet sample is introduced close to the outer electrode. Then, due to different dielectrophoretic mobilities, fibers of different lengths migrate radially at different velocities. They reach the inner electrode at different axial distances from the inlet. After separation, fibers can be recovered from the inner electrode. They could separate fibers down to 8 µm in length. The
Baron separator design was later optimized [148,154] and the device has been used by the US National Institute of Occupational Health and Safety (NIOSH) for the preparation of samples for in vitro testing of the influence of fiber length on toxicity [155].

Motivated by the Baron separator, we theoretically investigated the possibility to classify spherical airborne particles smaller than 10 µm using DEP [156]. Such fine particles find application in coatings, printing products, particle-reinforced polymers, or porous functional structures. Conventional classifiers, such as differential mobility analyzers or deflection wheel classifiers, suffer from low resolution below 10 µm. Further, electrophoretic mobility analyzers rely on particle charging. The particle-size-dependent charging probability shows a minimum between 100 nm and 1 µm, making this size range especially interesting. Our theoretical separator followed a similar concept as the Baron separator with a sheath flow and aerosol inlet flow and an outlet slit (Fig 7B). By varying gas flow rate and field strength, we could calibrate the separator for a specific particle size. We showed the theoretical possibility to classify particles with diameters from 20 nm to 90 µm at gas velocities from 0.1 cm/s to 514 cm/s and applied field strength of up to 30.5 MV/m.

4 Discussion and conclusion

Dielectrophoresis has come a long way since its first application in 1924 for the separation of minerals. After the early applications—in which macroscopic sheets and wires were employed as electrodes—its very unique qualities together with the “lab-on-a-chip”-boom ensured that is now one of the most promising techniques to be applied in many pressing biomedical separation tasks. Slightly contrasting to this development, in this review we collected applications of dielectrophoresis outside of the biological and biomedical sector. We explored some of the older applications of dielectrophoresis, with two of them even commercialized (i.e., Hatfield’s mineral separator and the Gulftronic DEP filter), one long before dielectrophoresis was the accepted term for the effect. This is in slight contradiction to the view that DEP has only recently made it to commercialization (see Hughes’ review from 2016 [5]) and agrees well with our perception that many of the studies discussed in this review—such as Baron’s fiber separator [153] or Fritsche’s DEP Filter [90]—are much less prominent compared to counterparts from the biomedical field. In our group, we research the feasibility to use DEP as a separation force in industrial applications. In an attempt to make DEP attractive to a wider audience, we encourage researchers to explore some of the lesser-known DEP applications which can result in promising applications off the beaten track.

The next steps for some of the presented studies are straightforward. Examples for this are the application of nDEP to prevent membrane fouling [135], in which a miniaturization of the employed electrodes gives promising results, and the separation of carbon nanotubes into metallic and semiconducting fractions [115], which requires more research in the design of suitable microfluidic separators. The outlook for some other applications is more clouded. Especially, the classification of particles at relevant throughputs is problematic. This is because (selective) separation of particles at relevant throughputs usually requires the application of strong electric fields to create sufficiently large forces. This is inevitably linked to detrimental side effects when applied in aqueous suspensions such as flow vortices caused by Joule heating-induced temperature differences or bubble generation. The consequence is that relevant throughputs should either be small, which is the case for the classification of highly-valuable products. Examples are again the binary sorting of carbon nanotubes into metallic and semiconducting fractions and the recovery of LbL-produced nanocapsules [82]. The other option is that the separation is possible in non-conducting media—with a prime example being the Gulftronic separator that is still commercially available [157]. Naturally, aqueous media are preferred in many applications due to a higher flexibility. A possible bridge over the throughput gap might lie in aqueous DEP filters [81] which give promising results for selective particle capture at high throughput. The high selectivity and controllability of DEP filtration could allow more flexible applications compared to conventional industrial separation methods. It is clear that such separators will never reach the selectivity as some state-of-the-art microfluidic DEP separators. As obvious from the many examples cited in this work, the requirements decide on the applicability of technology. DEP can offer an alternative in industrial applications where high product volumes are the priority and sorting accuracy is secondary. Of course, the trade-off between throughput and accuracy has to be kept in mind, similar to all other DEP applications. We expect that DEP can have more applications outside of the biomedical sector.

We thank Aswin Muralidharan (Delft University of Technology), Jasper Giesler, and Laura Weirauch (both University of Bremen) for careful proofreading of the manuscript. We further express our gratitude to Hui Zhao (University of Nevada, Las Vegas) for his input on the polarization models of non-conducting particles and to Pablo García-Sánchez (Universidad de Sevilla) for his input on the polarization of metal particles.

The authors have declared no conflict of interest.

5 References

[1] Hatfield, T. S., Trans. Inst. Mining Metall. 1924, 335–342.
[2] Pohl, H. A., J. Appl. Phys. 1951, 22, 869–871.
[3] Pohl, H. A., Hawk, I., Science 1966, 152, 647–649.
[4] Pethig, R., J. Electrochem. Soc. 2017, 164, B3049–B3055.
[5] Hughes, M. P., Biomicrofluidics 2016, 10, 032801.
[6] Li, M., Anand, R. K., Anal. Bioanal. Chem. 2018, 410, 2499–2515.
