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Recent progress and future opportunities in rheology: a review by the British Society of Rheology

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Rheology plays a critical role across science and engineering, affecting sectors from healthcare to energy. In the UK, rheological research supports innovation in both academia and industry. This review, coordinated by the British Society of Rheology (BSR), provides an updated overview of current research directions across the UK and beyond.

1. Introduction

Rheology is a multi-disciplinary field spanning science and engineering, with applications across materials science, geophysics, biology and medicine. In the UK, rheological research underpins key industrial sectors, such as food and beverage, energy, consumer goods and pharmaceuticals. The flow properties of everyday products—such as detergents and toothpastes—play a critical role in product performance and quality control, while rheology informs the handling of complex fluids in the energy sector.

The UK has a long-standing tradition of excellence in rheology, exemplified by figures such as Prof. J. G. Oldroyd (the father of the Oldroyd-A and Oldroyd-B models) and Prof. Ken Walters, the founder of the Journal of non-Newtonian Fluid Mechanics, a seminal journal in the field. The British Society of Rheology (BSR) founded in 1940, is a charitable society with 200 members worldwide, focusing on the science of the 'deformation of matter' and awarding several grants and awards including the BSR Gold Medal in recognition of outstanding contributions to rheology by scientists in the UK and internationally [1]. In 1964, the BSR published the first of a short series of reports[1] on the state of UK rheological research. Sixty years on, recognizing the evolution of the field—including the rise of new areas such as living and active matter—the BSR has revisited the 1964 initiative. Through a community-wide survey and contributions from its members, we have compiled this new report to highlight general advances in the UK and worldwide, affecting research in academia and industry. We cover fundamental topics, namely, the present state of the art in current rheological experimental techniques for macroscopic (§2) as well as microscopic (§3) length scales, and emerging modelling approaches (§4). We then focus on several specific materials of wide interest in §5 (e.g. foams and foods). The application of rheology in natural systems is discussed in §6 (e.g. volcanoes and blood cells). Section 7 focuses on manufacturing including three-dimensional printing as well as industrial rheological research. Finally, §8 presents the conclusions and future perspectives. We hope this report will foster future collaboration and accelerate progress towards addressing major societal and sustainability challenges.

2. Rheological techniques

(a) Advanced bulk rheology

Advanced bulk rheology encompasses experimental strategies that extend the measurable time or frequency range of traditional oscillatory and steady-shear tests, providing faster and broader characterization of the nonlinear and linear viscoelastic (LVE) properties of materials. Recent innovations have focused on broadband methods, such as iRheo [5] and optimally windowed chirp rheometry (OWCh) [6]. Both approaches can be implemented on most commercial rheometers and are increasingly being incorporated natively by instrument manufacturers. These broadband protocols offer significant advantages in time and frequency resolution, making them well-suited

[1]These surveys were undertaken jointly with the National Engineering Laboratory (NEL) and published biennially as NEL reports 165, 292, 408 and 493 (and possibly 572), with a restricted circulation. Three are summarized in [2–4].

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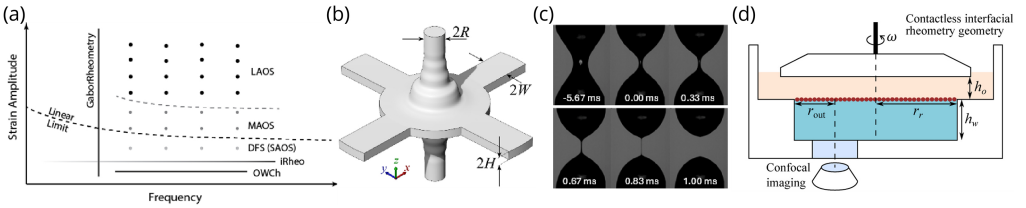


Figure 1. Rheological techniques. (a) Pipkin diagram comparing the frequency–strain amplitude trajectories and regions of interest for the advanced rheometric techniques discussed in this article. The axes are shown schematically; the boundaries between DFS (SAOS), MAOS and LAOS are material-dependent and do not correspond to universal values of strain amplitude or frequency. (b) Sketch of a stagnation point extensional flow rheometer, adapted from [14] published under Creative Commons license (CC BY 4.0). (c) Capillarity-driven break-up of an inkjet fluid, reprinted with permission from [15], Copyright 2010, The Society of Rheology. (d) Sketch of a contactless interfacial rheometer, adapted from [16] published under Creative Commons license (CC BY)

to transient or weakly aging systems and to efficient LVE characterization across a wide range of materials. The optimized chirp approach has also been extended to high-frequency piezo-driven applications [7] and to superposition rheometry [8], while the same windowed chirp concept has also been implemented in the dynamic mechanical analysis (DMA) environment [9]. In practice, iRheo provides time–frequency conversion of linear viscoelastic data obtained from stress relaxation or creep tests, whereas OWCh enables rapid frequency sweeps in oscillatory mode; together, they exemplify how broadband methods can accelerate rheological characterization without compromising accuracy.

Exploration of nonlinear response regimes using large- and medium-amplitude oscillatory shear (LAOS/MAOS) has become routine across soft matter systems from polymers [10] to food [11]. Consensus on a unified analysis framework remains elusive, but recent studies show that both the Fourier/Tschebyshev decomposition and the sequence of physical processes (SPP) frameworks yield complementary and self-consistent insights [12]. Gaborheometry [13] represents a more recent development that utilizes a short-time Fourier transform with amplitude-modulated waveforms (sweeping from linear to nonlinear strain amplitudes), enabling simultaneous time- and frequency-resolved analysis of medium-amplitude responses. The capabilities of these new rheometric tools are naturally considered in the context of a Pipkin diagram (figure 1*a*), relating the imposed frequency and imposed signal amplitude (this may be stress amplitude or strain amplitude depending on the specific device). The well-known small-amplitude oscillatory shear (SAOS)/MAOS/LAOS protocols are sequenced techniques that produce arrays of discrete data points at specific frequencies and progressively larger amplitudes. By contrast, both the OWCh and iRheo techniques are frequency-modulated protocols that sweep out horizontal lines in the linear viscoelastic regime, whereas Gaborheometry is an amplitude-modulated technique that sweeps out a vertical line in the Pipkin diagram spanning the linear and nonlinear regimes.

Superposition rheometry remains a valuable tool for probing nonlinear behaviour of structured fluids. While parallel and orthogonal superposition capabilities have existed for several years [17], orthogonal accessories are becoming more widely available and accepted [18]. Recent theoretical work has considered the interpretation of parallel superposition data across constitutive models and established frameworks for converting between parallel and orthogonal moduli, though such analyses remain model-specific. It should be emphasized that caution must be exercised when interpreting superposition moduli, as their underlying response spectra do not share the same physical meaning as the classical relaxation spectrum [19].

Ongoing developments in the electromechanical performance of modern rheometers continue to expand the accessible range of deformation protocols and dynamic range within the Pipkin space. These advances will ultimately support a rheo-informatics framework in which automated torsional instrumentation replaces traditional high-throughput viscometry [20], providing large, standardized datasets for the training and validation of digital fluid-twin models [21].

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(b) Extensional rheology

The Rayleigh–Ohnesorge jet extensional rheometer (ROJER) and its advanced version, ROJER-X, are instruments developed to overcome the limitations of traditional capillary break-up methods such as capillary break-up extensional rheometry (CaBER) [22]. ROJER employs mechanically resonant jet break-up combined with stroboscopic imaging to quantify the thinning dynamics of low viscosity filaments with high temporal resolution . By analysing a train of identical droplet formation events, the method yields statistically reliable measurements of filament lifetime and extensional relaxation behaviour while requiring minimal optical complexity. These features make it particularly suitable for investigating sprays and dispensing processes relevant to industrial and consumer formulations.

The original ROJER enables repeatable characterization of filament-thinning dynamics and extensional viscosity using droplet streams with well-controlled break-up behaviour [23]. The ROJER-X system extends this capability through orthogonal imaging and integrated control, enhancing data precision and experimental reproducibility. Its microsecond temporal resolution allows relaxation times to be determined without the need for high-speed cameras, facilitating detailed studies of transient extensional flows.

Further development of the technique could broaden its applicability. Priorities include automating imaging and data extraction to support adaptive experiments, and incorporating temperature and humidity control for volatile or multi-component formulations. Such advances would expand the range of measurable materials and strengthen the relevance of ROJER methods across both academic and industrial rheology.

The 'optimized shape cross-slot extensional rheometer' (OSCER) was developed through numerical optimization of the canonical planar cross-slot geometry (figure 1*b*) [24]. By coupling an automatic mesh generator, a fluid-flow solver and an optimizer, the design objective was to produce a flow with an extended region of homogeneous planar extension—an essential condition for extensional rheometry. An experimental realization [25] confirmed that the device achieves this kinematic uniformity under Newtonian creeping-flow conditions, with a broad region of constant extension rate around the stagnation point. For viscoelastic fluids, where polymers stretch above the Weissenberg number $Wi \sim 1$, this homogeneous region narrows, but the strain rate and stress along the stretching axis remain approximately uniform [25]. Birefringence and pressure-drop measurements in the OSCER have been used to determine extensional viscosities of low viscosity complex fluids [25] and to study the onset of elastic instabilities in viscoelastic flows [26].

The OSCER geometry has also been applied to probe yielding in elastoviscoplastic (EVP) materials [27]. Extensional yield stresses can exceed their shear counterparts, with the ratio governed by yield strain—a key factor for constitutive modelling. The addition of polymers enhances the elastic response in extension, an effect absent in shear, with implications for additive manufacturing (AM) and the processing of structured fluids. Furthermore, OSCER has been employed to examine orientational dynamics of rod-like colloids in extensional flows, relevant to the fabrication of soft materials with controlled microstructure [26].

Building on this platform, three-dimensional optimized geometries have been developed; most notably the six-arm cross-slot [28]. The resulting *optimized uniaxial and biaxial extensional rheometer* (OUBER) generates near-homogeneous uniaxial and biaxial stagnation-point flows, operating on principles similar to OSCER. A recently derived power balance for these devices demonstrates that the excess pressure drop is directly related to the principal stress difference via a numerical prefactor linked to the fluid volume over which the flow remains homogeneous [14]. For Newtonian or weakly viscoelastic fluids ($Wi \lesssim 1$), this volume of homogeneous flow approaches the device geometry, whereas at higher Wi, it contracts to a narrow stagnation region where polymers are strongly stretched. Measurements from OUBER and OSCER, evaluated using this power balance, yield extensional viscosities consistent with FENE-P predictions based on measurable fluid parameters and polymer extensibility.

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Recent work has extended the OSCER concept to large-amplitude oscillatory extension experiments on dilute polymer solutions [29]. By imposing sinusoidal extension-rate profiles and measuring the resulting pressure response, this approach provides a means to characterize nonlinear viscoelastic behaviour under controlled extensional deformation.

Achieving steady extensional flow curves requires maintaining flow homogeneity over a range of strain rates and measuring the principal stress difference at steady state—analogous to conventional steady-shear measurements. For low viscosity fluids, OSCER and OUBER currently represent the most direct route to this goal. A persistent challenge remains sustaining flow homogeneity beyond $Wi \gtrsim 1$, where polymer stretch induces localization of the region of highly elongated material. Improved understanding and control of this transition, together with exploration of complex polymer architectures such as star-shaped, pom–pom or ring polymers, are expected to advance the quantitative reach of extensional rheometry.

TriPAV and TriMaster are compact rheometric platforms that extend the accessible frequency and strain-rate range for the characterization of low viscosity and microvolume samples. While conventional rotational and capillary rheometers remain essential tools, their limited frequency window and relatively large sample volume requirements restrict their use for delicate or scarce materials. Recent advances in piezoelectrically actuated and filament-thinning techniques [30] have opened new opportunities for probing viscoelastic behaviour across previously inaccessible regimes.

The *TriPAV* system, derived from the Pechhold piezo axial vibrator concept [31], employs nanometric piezoelectric actuation to measure fluid responses over an exceptionally broad frequency range, from 1 Hz to 10 kHz, using only microlitre-scale samples. This enables accurate determination of the linear viscoelastic properties G', G'' and η^* across a wide dynamic spectrum, providing valuable data for materials such as biofluids, polymer solutions and nanostructured liquids. Although primarily a high-frequency shear rheometer, its capabilities complement bulk and extensional measurements by bridging the gap between acoustic and mechanical regimes.

The *TriMaster* builds upon early filament-thinning devices [32] and the Cambridge MultiPass Rheometer [33] to achieve precise extensional characterization via symmetric opposed-piston motion. Filament evolution is tracked using high-speed imaging (figure 1*c*) [15], allowing direct determination of extensional relaxation times and viscosities. This configuration has been applied to inkjet formulation studies and is now being explored for biopolymer and soft matter systems [34]. The technique offers a controlled and reproducible approach to studying filament dynamics in low viscosity fluids, complementing jet-based methods such as ROJER.

Future developments are expected to enhance the versatility of both instruments. For TriPAV, refinements in temperature control, calibration and signal processing could further improve accuracy at high frequencies. For TriMaster, automation of image analysis, adaptive piston control and integration with complementary measurement modalities (e.g. optical or spectroscopic techniques) would broaden its applicability to viscoplastic and thixotropic materials. Together, these compact systems exemplify ongoing progress towards faster, more precise rheological characterization across a wide range of materials and time scales.

(c) Interfacial rheology

Interfacial rheology seeks to measure the mechanical properties of liquid–air and liquid–liquid interfaces, often decorated with surfactants, proteins or colloidal particles [35]. Measurements are often classified as dilatational rheometry (changing area at constant shape), including pendant-drop tensiometry, or shear rheometry (changing shape at constant area), including the magnetic needle surface rheometer and the double-wall ring rheometer [36], even though some techniques are strictly speaking mixed-mode, for example, Langmuir-trough measurements when using straight barriers [37]. Interfacial microrheology is another technique for measuring the mechanical properties of viscoelastic interfaces, though it can be challenging to rationalize discrepancies between interfacial microrheological and macrorheological measurements [38].

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Recent years have seen substantial progress in understanding the rheology of complex fluid–fluid interfaces, both on the theoretical side [39] and on the experimental side (figure 1*d*) [40]. For example, Langmuir-trough and pendant-drop measurements are well-established for surfactant-laden interfaces, but recent theoretical and computational efforts attempt to extend the applicability of the techniques to situations in which deviatoric and anisotropic interfacial stresses may develop [41,42]. More recently, machine learning (ML) has appeared as an additional tool, for example, the use of convolutional neural networks (NNs) to extract surface tension or interfacial tension from images of axisymmetric pendant drops [43]. In terms of instrumentation, recent advances include both refinements of established methods and the development of entirely new techniques to overcome their limitations. For example, a radial trough has been introduced to address the mixed-mode nature of traditional Langmuir-trough measurements [37]. Other efforts focus on combining complementary methods to provide a more complete characterization of interfacial rheology, such as the Quadrotrough, which enables independent dilatational and shear deformations at the liquid–air interface [44], the integration of a double-wall ring geometry with neutron reflectometry [45] and the coupling of a double-wall ring geometry with a confocal microscope [46]. More recently, researchers have also developed 'contactless interfacial rheology' methods, to measure interfacial mechanical properties without having a (macroscopic) probe in the interface. Muntz *et al.* [16] shear the top liquid phase and measure the interfacial response using confocal microscopy, though they note that, in principle, a fixed-rate motor combined with reflection or fluorescence microscopy should suffice. Venerus [47] has suggested an alternative non-invasive approach, called the rotating cone interfacial rheometer, for the flow of a Newtonian liquid between a rotating cone and a planar, gas–liquid interface; though no experimental results are presented [47], the flow modelling results for viscous, shear-thinning and yield-stress interfaces look promising.

A remaining challenge for interfacial rheology is the connection between interfacial-rheology measurements and the characteristics of the corresponding macroscopic materials. For example, linking the interfacial rheology of a particle-laden water–oil interface to the characteristics of the corresponding Pickering–Ramsden emulsion is still challenging [36]. One major challenge is sample history, as this can affect both the interface-rheological measurement and the macroscopic material, so if those two measurements are performed separately, then the two shear histories have to be equivalent, which can be challenging to achieve. This is another reason for further development of contactless and/or *in situ* interfacial-rheological techniques.

(d) Chemical exchange rheology

A significant drawback of current paradigms in rheology is that the samples being tested are typically probed under chemical equilibrium. While this greatly simplifies the interpretation of rheological data, it sidesteps the important question of how the rheology of the sample changes during changes in chemical environment. Understanding this question is essential for exploring fundamental industrial, biological and material properties. As an example, consider the rheological properties of the collagen fibres that constitute tissue, which withstand chemical degradation from physiological enzymes under high strains but are destroyed under low strain [48]. This 'use it or lose it' functionality can only be rheologically probed under conditions when chemistry and shear are accessible simultaneously. Analogies can be drawn with equivalent fundamental problems in industrial mixing, chemical formulation, food digestion and biomaterial design.

To address this, many researchers have developed approaches that combine chemical exchange with rheological characterization. Typically, the sample is isolated from a chemical reservoir using a series of holes, a moistened plate or a semi-permeable membrane, which is mounted on the lower plate of a parallel plate rheometer [49]. In one example, a modified rheometric set-up was used to induce the gelation and degradation of alginate solutions under changing ionic strength, enabled by a dialysis membrane mounted on the rheometer's lower plate [50]. Similar approaches have been used to probe drug release profiles of alginate hydrogels by chemically

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characterizing the products of the hydrogel degradation through a sample port, which is novel in the sense that the rheological properties and chemical environment can be probed and correlated simultaneously [51]. Further refinements have been constructed for such systems, which incorporate syringes, peristaltic pumps and different pore sizes and distributions to control the rate and spatial uniformity of chemical reactions during rheological testing. Equivalent devices have been constructed for particle tracking microrheology where the chemical environment is changed through the incorporation of a semipermeable membrane in a microfluidic chamber. Alongside the lower sample volume that is intrinsic to all microrheology, this enables much higher throughput of measurement [52] and also allows for the study of specific phenomena not accessible by other techniques, such as degradation and disassembly kinetics, reversible phase behaviour and automated compositional control.

Significant technical challenges remain in adopting chemical exchange approaches at both microscopic and bulk scales. Chief among these is preventing sample loss from the chamber during operation, along with understanding the impact of concentration gradients generated during external exchange. These issues pose both fundamental challenges and opportunities for studying rheology under realistic industrial and biological conditions. The main strength of such techniques lies in their versatility: in principle, they can be applied to any system accessible to conventional rheology or microrheology. Coupled with their high-throughput potential, they offer advantages over automated bulk rheology platforms, which are largely restricted to viscous samples that tolerate robotic handling. However, their broader adoption has been limited by technical complexity. The ultimate measure of their value will be their uptake beyond the laboratories where they originated.

(e) Non-invasive in-process rheology by acoustical technologies

Traditional oscillatory rheometry and more recent ultrasound-based methods provide complementary insights into material behaviour. While oscillatory rheometry offers high-precision measurements under well-controlled deformation conditions, acoustic techniques enable in-line, in-process access to key material properties—such as viscosity, rigidity, compressibility and bulk modulus—without interrupting flow or processing conditions.

Ultrasound attenuation measurements respond to the complex viscosity, which comprises the storage modulus (elastic response) and the loss modulus (viscous response). Accordingly, the relationship between the longitudinal fluid viscosity η_{long} [Pa s] and longitudinal sound attenuation α_{long} [Np m^{-1}, where Np is the dimensionless unit Neper] is

$$\alpha_{\text{long}} = \frac{\eta_{\text{long}}\omega^2}{2\rho c_{\text{long}}^3}\left(\frac{4}{3} + \frac{\eta_B}{\eta_{\text{long}}} + \frac{(\gamma-1)\kappa}{\eta_{\text{long}}C_p}\right), \tag{2.1}$$

where γ is the ratio of specific heats, ρ [kg m^{-3}] is the density, κ [W m^{-1}K^{-1}] is the thermal conductivity, C_p [J K^{-1}kg^{-1}] is the specific heat at constant pressure, ω [rad s^{-1}] is angular frequency, η_{long} [Pa s] is the longitudinal viscosity, c_{long} [m s^{-1}] is the longitudinal sound speed and η_B [Pa s] is the bulk (volumetric) viscosity [53, ch. 6: propagation in viscous and thermally conducting fluids].

An example of how ultrasound rheology is complementary to conventional oscillatory rheology is the case of anhydrous milk fat (AMF), a material that transitions from a liquid to a soft solid upon cooling [54]. Rheological and acoustic measurements were used to study the crystallization process of AMF. The results show that as AMF cools, it forms crystal clusters that significantly impact its mechanical properties. The study demonstrates how acoustic and rheological data can be used together to determine both low- and high-frequency rheological measurements in heterogeneous systems like AMF.

One of the most attractive aspects of acoustic rheology is its application in real-time non-contact industrial process monitoring. Recent developments in this field include passive acoustic emission sensing described by Hefft *et al.* [55], where two surfactant-based structured fluids exhibiting

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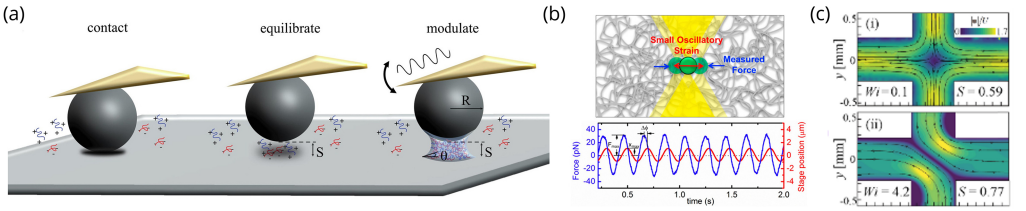


Figure 2. Microrheology and microfluidics. (a) Protein condensate rheology studied using a spherical probe on an atomic force microscopy (AFM) cantilever, adapted from [57] published under Creative Commons license (CC BY 4.0). (b) Sketch illustrating oscillatory microrheology, adapted from [58] published under Creative Commons license (CC BY). (c) Planar extensional flow in a cross-slot geometry, adapted from [59] published under Creative Commons license (CC BY 4.0)

complex non-Newtonian rheology were studied on a laboratory and pilot manufacturing scale using an *in situ* rheometric device and ML. Another interesting application was shown by Bowler *et al*. [56], who used low-cost, inline ultrasonic sensors to characterize honey–water blending and flour–water batter mixing, demonstrating its utility in food manufacturing processes.

The combination of rheology and acoustics thus provides a comprehensive understanding of the mechanical properties of soft solids. Acoustic techniques facilitate the application of rheological methods by offering non-invasive, inline measurements that can be integrated into industrial processes. This approach is valuable for studying the texture and quality of foods, as well as for applications in biomedical engineering and material design.

3. Microrheology and microfluidics

(a) Microrheology

Microrheology leverages rheological principles to investigate materials at micron and submicron length scales (figure 2*a*,*b*) [57,58]. Compared to conventional techniques, it offers several key advantages: (i) it requires minimal sample volumes (a few tens of microlitres), making it particularly valuable for biophysical studies, (ii) inertial artefacts arise only at significantly higher frequencies (approx. MHz), owing to the small sample volumes and the low mass of the probes, and (iii) it provides exceptional sensitivity, enabling measurements of forces in the picoNewton range, displacements at the nanometre scale and temporal resolutions down to microseconds.

Most microrheology techniques rely on tracking the motion of micron-sized probe particles embedded within the sample. These methods are broadly classified as either *passive* or *active*, depending on whether the motion of the probes is driven by thermal fluctuations or externally applied forces, respectively. While the origins of microrheology can be traced back to Robert Brown's 1827 discovery of Brownian motion, the field was formally established in 1995 with the seminal work of Mason & Weitz [60], who introduced a quantitative framework for extracting viscoelastic properties from particle trajectories.

Since then, advancements in particle tracking, optical tweezers, magnetic tweezers, dynamic light scattering, diffusing wave spectroscopy and atomic force microscopy (AFM) have significantly expanded the scope of microrheology, enabling applications across physics, materials science and biology. For a comprehensive overview and understanding of the most common microrheology techniques, the reader is referred to the review articles [58,61]. Recent research in marine microbiology has uncovered microscale viscosity gradients surrounding phytoplankton, with profound implications for global biogeochemical cycles [58]. In medical research, microrheology has transformed our understanding of bacterial biofilms, revealing that biofilms grown *in vivo* exhibit greater elasticity than their *in vitro* counterparts—a discovery that could inform new approaches to infection control [62].

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Microrheology is also shedding light on cancer progression. In breast cancer models, researchers have used force spectrum analysis to reveal a paradoxical mechanical response: tumours both stiffen and fluidize their ECM, enabling invasion while maintaining adhesion [63]. Similarly, in biomaterials research, high-throughput microrheology has been employed to optimize the gelation kinetics of protein hydrogels, aiding the development of advanced materials for drug delivery and tissue engineering [64].

At the molecular level, microrheology has been instrumental in studying protein condensates—membraneless organelles that play a crucial role in cellular organization (figure 2*a*) [57]. Researchers have quantified their viscoelastic properties, shedding light on their role in neurodegenerative diseases [57]. In addition, in the field of aging and mechanobiology, time-shared optical tweezer microrheology has allowed scientists to probe how intracellular mechanics evolve with age, revealing that mutations in nuclear envelope proteins lead to cytoplasmic softening, potentially linking mechanical properties to aging-related disorders [65].

These diverse applications underscore the versatility of microrheology in addressing complex biophysical questions. Bridging length scales and capturing dynamic mechanical behaviours with high sensitivity, techniques such as these continue to unlock new frontiers in biology, medicine and materials science. A recent example is the work of Mendonca *et al.* [66], who combined optical tweezers with microfluidics to probe the role of the mitotic chromosome periphery. Their analytical approach enabled broadband microrheology across seven decades of frequency, up to 10^5 rad s^{-1}. This revealed key mechanical features of single chromosomes and demonstrated the potential of microrheology to explore previously inaccessible chromosomal structures.

Recent advances in ML are poised to revolutionize microrheology, particularly by addressing the long measurement times typically required for passive techniques, which rely on statistical analysis and large datasets. These extended durations are often impractical in biological and biomedical contexts, where rapid assessments are essential. ML, especially physics-informed ML, holds the potential to drastically reduce measurement times while maintaining high accuracy. Notably, ML has already demonstrated its ability to extract viscosity properties from just 1 second trajectories [67], significantly enhancing the efficiency of microrheology. This advancement paves the way for faster and more effective applications in intracellular mechanics, biomolecular condensates and real-time tissue diagnostics. The incorporation of rheological models into ML algorithms is expected to further improve both accuracy and interpretability, driving the future development of microrheology for non-Newtonian fluids and real-time biomedicine and materials science applications.

(b) Microfluidics and instabilities

Flow instabilities driven by fluid elasticity are rich in nonlinear dynamics [59]. Although such instabilities can also occur at the macroscale, owing to the small length scales, and hence high shear rates, they are particularly important at the microscale. The onset of instability can drive a viscoelastic flow to bifurcate through time-steady, periodic, quasi-periodic, aperiodic or chaotic (i.e. rheochaos or elastic turbulence) states (figure 2*c*) [59]. Instability may be undesirable (e.g. in the case of microfluidic rheometry), but it is often exploited in, for example, flow control, enhanced mixing, dispersion, heat transfer and reaction rates, drag reduction and the mobilization of trapped oil in subterranean reservoirs. Understanding, and controlling the onset of, elastic flow instabilities is therefore of great academic interest and industrial importance (e.g. the recent review by Datta *et al.* [68]). The onset of an important class of instability is driven by the generation of elastic tensile stress along curving streamlines, as described by a criterion introduced by McKinley *et al.* [69].

Steady flow asymmetries: elastic-driven instabilities resulting in steady asymmetric flows of viscoelastic fluids above a critical Weissenberg number have been observed in a range of geometries, including cross-slots, T-junctions and flow-focusing devices [70]. A steady flow asymmetry has also been recently observed for viscoelastic flow past quasi-two-dimensional cylinders in

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microchannels with low blockage ratios, resulting in more flow around one side of the cylinder than the other [71]. This flow asymmetry is initially driven by random flow perturbations owing to increased elasticity downstream of the cylinder, in accordance with the Pakdel–McKinley criterion. However, shear-thinning of the fluid plays an important role by acting to keep the flow steady on the selected branch of the bifurcation. A similar mechanism may also control a more well-known steady flow asymmetry observed in the cross-slot microchannel [70].

Control by geometric and fluid properties: recent efforts have been exerted in controlling the appearance of these asymmetries, so far mainly by passive means, through both geometry and tailoring fluid properties. The use of the prototypical cross-slot microchannel has proven useful here. In [72], a cylinder was added to the geometric centre of the cross-slot, changing the fundamental nature of the stagnation point. Simulations found that larger diameter cylinders were able to successfully delay the onset of the steady asymmetry by about a factor of 2 in the flow rate, in qualitative agreement with experiments. Interestingly, although the addition of the cylinder significantly changed the flow distribution near the stagnation point for low blockage ratios, the critical condition for onset remained unchanged in this limit, suggesting that the instability may be a classical 'curved streamlines' one rather than owing to the stagnation point *per se*. In follow-up work [73], injecting two fluids with different elastic properties from each inlet arm was shown to be an effective approach to stabilize the purely elastic instability, based on the properties of the fluid with the larger relaxation time. Increasing interfacial tension between the two fluids also contributed to flow stabilization.

Three-dimensional viscoelastic flows: tomographic particle image velocimetry has enabled quantitative and time-resolved visualization of purely elastic flow instabilities in three-dimensional microchannels. For instance, it was shown that the resulting time-dependent motion of two passive flexible cylinders in a microchannel can become coupled through elasticity [74]. Scaling this up to large arrays of passive flexible structures has led to the concept of viscoelastic canopy flow. It has been shown that even in the absence of inertia, Monami-like waves can develop over the surface of the canopy concomitantly with the onset of elastic turbulence [75]. Study of this coordinated motion driven by viscoelastic flow may inform better understanding of the reverse problem of a viscoelastic flow (e.g. of mucus) being driven by coordinated motion of structures (like cilia). Viscoelastic canopy flow involves the interplay between multiple complex phenomena: viscoelastic porous media flow, viscoelastic fluid–structure interaction, elastic instabilities and elastic turbulence and a possible mixing (shear) layer at the canopy surface where the flow profile develops an inflection point [75]. There may be multiple factors that can influence the observed dynamical phenomena through and over the canopy, including the height of the canopy relative to the confining channel, the density of the canopy, the arrangement and flexibility of the structures in the canopy and of course the fluid rheology. We have only just begun exploring the vast parameter space of this extremely interesting but complicated system.

(c) The microrheometer

Despite their versatility, conventional rheometers encounter sensitivity limitations when analysing weakly viscoelastic liquids [76]. This presents a significant challenge, as many biological fluids—such as saliva, blood plasma and synovial fluid—exhibit low, yet physiologically meaningful, viscoelasticity [77]. For example, elevated fibrinogen levels in plasma, which affect its rheology, have been linked to conditions like chronic obstructive pulmonary disease (COPD), stroke and sepsis [78].

Microfluidic technologies, such as the microrheometer, provide promising solutions to this measurement gap. The microrheometer works by exploiting the lateral migration of rigid particles suspended in viscoelastic liquids flowing through a circular microfluidic channel [79]. Owing to normal stress differences, particles migrate towards the centreline, and the fraction of particles aligned at a fixed distance from the inlet is directly related to the fluid's longest relaxation time. In addition, the velocity of particles at the centreline can be used to estimate the maximum fluid

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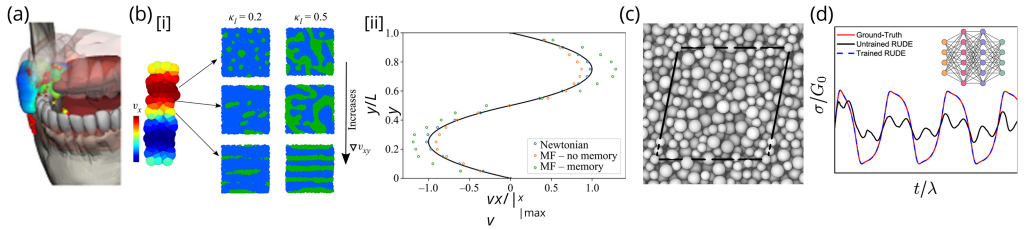


Figure 3. Modelling rheological phenomena. (a) Modelling the breakdown of agar gel during chewing, adapted from [81] reproduced with permission (c) 2014 Wiley. (b) Simulated multi-phase flow using a heterogeneous multi-scale method, adapted from https://arxiv.org.pdf/2211.05080 CC-BY, [82]. Shown are [i] snapshots of the simulated system for different model parameters, and [ii] simulated velocity profiles. (c) Example of a discrete element method (DEM) simulation typically used for studying granular rheology. (d) Rheological prediction made by ML-based model.

velocity and, using the Hagen–Poiseuille law, calculate viscosity—provided that the pressure drop is controlled via a pressure pump. This ability to extract both viscosity and elasticity from a single, rapid measurement is a key advantage. The microrheometer has proven highly sensitive across a variety of samples (see the review article [76] and references therein). It has been applied in studies of polyelectrolytes and polymerized ionic liquids, where its data supported bulk rheology results and contributed to the development of a new scaling law applicable in high-salt conditions, where classical Debye–Hückel theory breaks down. Its measurements have also been validated against the OSCER device described earlier, confirming its accuracy across different systems. Beyond sensitivity, the microrheometer offers practical advantages. It avoids many limitations of traditional rheometers, such as surface treatment requirements or large sample volumes. Its microfluidic design enables fast measurements with high precision, and recent developments have introduced temperature-dependent operation. In these experiments, both viscosity and relaxation time data showed strong agreement with bulk rheology and theoretical polymer physics predictions, further validating the platform's robustness. Notably, the same study presented a biomedical proof-of-concept, using the microrheometer to evaluate model solutions of hyaluronic acid as a proxy for synovial fluid in knee joint grade assessments. With only 100 µl of sample and a measurement time of under 2 minutes, the device demonstrated its suitability for healthcare applications. Many physiological fluids are only weakly viscoelastic and limited in volume, making this capability particularly valuable.

While the microrheometer has primarily contributed to soft matter and polymer physics, its most compelling future lies in clinical diagnostics. It is particularly suited to conditions, such as inflammation or sepsis, where elevated fibrinogen levels change plasma viscoelasticity [77]. Very recently, rapid measurement of viscosity and relaxation time using the microrheometer in the clinical setting was presented in the context of COPD patients [80]. Similar works on other diseases coupled to increased patient pools could provide clinicians with critical information for early intervention.

4. Computational modelling approaches

(a) Numerical simulation of complex fluids and flows

Advances in constitutive modelling, a greater understanding of the properties of mathematical models and access to high-performance computing platforms have contributed to significant developments in the design and implementation of numerical methods for simulating viscoelastic fluids. Stabilization strategies like the log-conformation formulation have effectively consigned the high Weissenberg number problem, in which stresses became unbounded and simulations failed to converge for Weissenberg numbers of order 1 or larger, to history, while quantitative agreement between experimental and numerical simulations has been obtained for both polymer

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melts through improved models of polymer dynamics, and polymer solutions through careful fitting of model parameters to experimental data. New mesh-free methods have been gaining popularity. Particle-based methods such as smoothed particle hydrodynamics (SPH) (figure 3*a*) [81] are now capable of robust simulations of free-surface viscoelastic flows at high elasticities, and mesoscopic methods such as smoothed dissipative particle dynamics (SDPD) can accurately predict the rheology of complex colloidal suspensions over a broad range of concentrations (figure 3*b*) [82]. Other recent advances include ML-assisted methods for parameter estimation and reduced-order modelling.

Quantitative agreement between a range of polymer melt experiments and numerical simulations was achieved using tube-based models such as the pom-pom and Rolie-Poly models. Polymer solutions were less tractable until recently, when quantitative agreement with experiments has been achieved even in multi-phase flows. For example, the dynamics of rising bubbles has been studied experimentally and the parameters in the exponential Phan-Thien–Tanner model determined to fit the experimental data, leading to numerical simulations (e.g. [83]) which have accurately predicted the 'jump discontinuity' in the bubble rise velocity.

Improvements in computer power have opened more possibilities for methods, such as two-fluid, volume-of-fluid (VOF), level set and interface tracking methods. Commercial finite volume (FV) solvers can now handle large industrial problems with complex geometries, taking up less memory than finite element solvers and incorporating adaptive mesh refinement, VOF methods, adaptive time-stepping and interface tracking [84]. Another major recent change has been the widespread adoption of the open-source FV solver RheoTool [85], based on the OpenFOAM platform, which has made complex fluid modelling accessible to a much wider range of researchers.

Two key advances in mesh-free simulation methods have been used to explore elastic instabilities in non-trivial geometries. An extensive body of work by Grilli *et al.* [86] uses weakly compressible variants of SPH that enforce the fluctuation–dissipation theorem using the general equation for non-equilibrium reversible–irreversible coupling (GENERIC) method; these methods do not require artificial stabilization strategies. The second approach involves sacrificing global conservation for methods that provide polynomially consistent reconstructions, typically in incompressible settings and incorporating the log-conformation approach. Recent progress includes a mesh-free method based on Cholesky decomposition yielding an order-of-magnitude improvement in resolving power [87]. This enables cost-effective simulations of elastic instabilities in non-trivial geometries, with accuracy comparable to high-order finite differences.

Recent advances in computational rheology have been driven by seeking quantitative agreement between experimental measurements and visualizations and computational predictions for a range of benchmark complex flow problems for polymeric fluids. There are opportunities to extend this methodology to complex multi-phase problems and particle suspensions, for example. The numerical treatment of deformable and mobile interfaces will be a critical challenge in this area, particularly for complex interactions involving multiple bubbles and droplets. Capturing complex flow phenomena, such as elastic turbulence, wall slip and shear banding, also demands enhanced numerical schemes.

In terms of accuracy and cost, mesh-free methods are currently lagging mesh-based approaches, but this could change with advances in particle splitting/coalescing schemes, which are yet to be applied to flows of complex fluids. While some (e.g. [87]) mesh-free formulations for viscoelastic flows avoid the use of artificial stress and artificial diffusivity for stabilization, many formulations do not, and a key goal for the community is to ensure that stabilization schemes do not contaminate the simulated physics.

In discrete materials, one promising direction is the use of particle-based discrete element method (DEM) simulations (figure 3*c*) to span between experiments (especially those using photoelasticity to capture particle stresses) and constitutive modelling. Such simulations allow highly resolved scrutiny of particle-level physics and dynamics and have led to many recent mechanistic insights [88]. In addition, it has been shown that suspensions can be modelled effectively with a two-fluid approach [89], solving the Navier–Stokes equations for each phase but applying the particle pressure only to the solid phase. The latter innovation allows for capturing particle phase

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migration, a phenomenon observed experimentally by Gadala-Maria & Acrivos [90] and in Stokesian dynamics simulations by Nott & Brady [91] and later quantified by Phillips *et al.* [92], and formalized into models in which gradients in the stress tensor govern the relative motion of liquid and solid phases. Capturing phase migration is an important step in understanding the rheology of heterogeneous systems in which gradients of composition and flow are present.

In SPH, the compromise between consistency and conservation remains, and the development of mesh-free methods exhibiting both high-order consistency and exact global conservation is an open challenge. Following the GENERIC framework, an important development in mesoscopic methods has been a fully Lagrangian multi-scale SDPD framework capable of capturing microscopic effects at the macroscale [82], allowing the simulation of complex flows at larger scales without the explicit imposition of a constitutive model. Further exploitation of the multi-scale nature of SDPD and related approaches is a promising avenue for mesh-free methods.

Across all simulation methods, establishing a comprehensive set of benchmark problems for experimental and computational study with opportunities for reporting on progress and comparing predictions will drive progress. Integrating multi-physics and multi-scale frameworks will be crucial for treating complex real-world systems. Efficient parallel computing strategies leveraging GPUs and distributed architectures will enhance scalability for these computationally intensive applications.

(b) Machine learning for constitutive model discovery and identification

Given the broad range of real-world fluids, a key hurdle for the rheologist is the identification and parametrization of an appropriate constitutive model for use as a predictive tool. The fast pace of artificial intelligence (AI) development, specifically in the fields of scientific ML and physics-informed NNs (PINNs), holds promise not only for automating this process, but more significantly for generating better model closures, as well as potentially unlocking new modelling paradigms and models.

A common use of AI in this area has been for model selection and parametrization. Two key recent contributions are 'ViscoelasticNet' [93] and the 'rheology informed NN' (RhINN) [94], which start either from only the velocity field, or from limited viscometric data, to select the best-fit model and its parameters.

In the area of constitutive model *discovery*, a key effort has been focused on developing model frameworks that can be learned from limited training data. More broadly, it is essential to ensure that the learned models are not confined to the specific experimental protocol on which they have been trained. Instead, they should be *transferable* and capable of accurately describing fluid behaviour across a wide range of flow conditions (for example, different kinematic histories). This is particularly challenging when simulating complex fluid flows, which often exhibit fading fluid memory effects arising from past deformations, making instantaneous-response models (e.g. generalized Newtonian fluids (GNFs)) insufficient. In this context, Lennon *et al.* [95] proposed the 'rheological universal differential equation' (RUDE). Training an NN using SAOS/LAOS synthetic data, they showed the ability of the RUDE framework to predict the material response in a more complex kinematic history corresponding to steady flow through a planar contraction. While these advances are promising, further developments are needed to extend the approach beyond single-mode Giesekus-like fluids and to enable robust predictions at higher Weissenberg number flows. A related approach by Shanbhag & Erlebacher [96] used sparse regression rather than a general NN to approximate unknown physics, with the advantage of predicting a closed-form model and improving the interpretability of the end result. The concepts embodied in sparse identification of nonlinear dynamics (SINDy) have also been adopted in the context of rheology, with Sato *et al.* [97] recently introducing Rheo-SINDy, in which the training process involves selection of a small number of dominant terms from a large library of candidate functions to arrive at a closed form constitutive model. Mahmoudabadbozchelou *et al.* [98] coupled SINDy-inspired

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regression with RhINNs, simultaneously optimizing a sparse regression-based constitutive model and an NN for computing the stress .

Recurrent NNs (RNNs) are particularly suited for discovering constitutive laws that capture thixotropic and viscoelastic behaviour given the natural time/history-sensitive nature of the recurrent units. Chen [99] investigated the potential of both RNNs and the more complex 'long short-term memory' unit, which uses gated mechanisms to control the flow of temporal information, showing promising extrapolation capabilities after training only on limited strain input protocols. Mahmoudabadbozchelou *et al.* [100] investigated a 'multi-fidelity' NN approach for viscosity prediction, recognizing the negligible cost of generating synthetic 'low-fidelity' data using a known constitutive model, as compared to the expense of obtaining high-fidelity experimental data. By first relating material characteristics, such as colloid fraction and sample age, to a classical rheological model using a low-fidelity NN, basic physical intuition is established which is then fine-tuned using a high-fidelity NN trained on experimental data to infer the viscosity of new samples with modified material characteristics, for example. This was extended by considering graph NNs in the design of 'rheology informed graph NNs' (RhiGNets) and multi-fidelity RhiGNets [21], facilitating so-called 'digital rheometers' with interesting capabilities in predicting the resulting shear stress responses for unseen rheometric protocols. Recognizing the limitation that an AI model trained on specific problems typically struggles to generalize beyond these, Mangal *et al.* [101] recently reviewed alternatives, such as Fourier neural operators, that can improve the generalization to unseen conditions.

It is worthwhile to emphasize that the vast majority of the above mentioned contributions incorporate physics-guided or physics-informed approaches, either by directly enforcing known physical equations (as in RhINNs and RhiGNets) during the training step, or by constraining the ML model architecture to encode a more favourable inductive bias so that the trained model output can more accurately represent the unknown physics (as in RUDE, RNNs and SINDy). In either case, the *a priori* insights of classical modelling approaches are crucial in ensuring the usability of the end result. We anticipate a continued symbiotic relationship between mechanistic and ML-based modelling approaches, and indeed, both can benefit one another as ML-based modelling insights, for example, via symbolic regression, may be incorporated into next-generation mechanistic models, and vice versa.

One of the key challenges in constitutive model discovery is ensuring that learned models obey the principle of frame invariance or *material objectivity*: this is crucial for ensuring model prediction of arbitrary deformation protocols, which in turn is vital for 'model portability', or the predictive capabilities of a newly trained model under previously unseen (large deformation) flow protocols. Equally important, most work has focused on learning single-mode differential models with one dominant material relaxation time scale, which is a coarse approximation for describing the broad spectrum of relaxation times characteristic of real-world fluids and aging systems. Finally, the field of model discovery needs to move beyond shear stress responses alone (figure 3*d*) to incorporate learned normal stresses and indeed extensional flow responses.

Considering more traditional PINNs that completely replace conventional computational fluid dynamics (CFD) solvers and predict stress and velocity fields directly, the step away from GNFs and linear thixotropic-elastoviscoplastic (TEVP) models and into frame-invariant formulations remains a challenge. A promising approach is the framework of Young *et al.* [102], which uses autoencoders to incorporate scattering intensity data with velocity field information to predict microstructural evolution of rigid rod suspensions. In recent years, there has been a major focus on using ML tools to accelerate calculations for turbulent CFD [103], but there has been comparatively little progress considering viscoelastic CFD solvers, which analogously involve additional unknown stress/velocity gradient relationships. The new approaches for learning key kinematic features of Newtonian turbulence could serve as a blueprint for improving the accuracy and efficiency of flow simulations of complex fluids.

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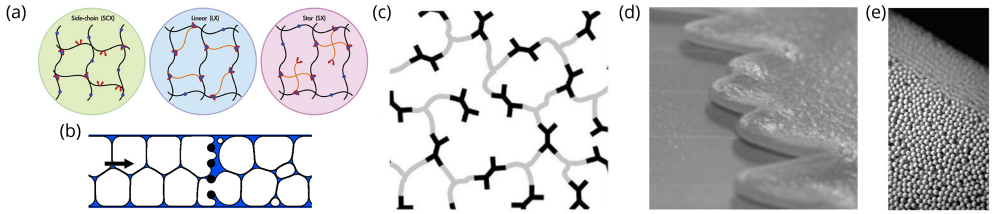


Figure 4. Rheology of complex fluids and soft solids. (a) Sketch of cross-linked hydrogels, published unde Creative Commons license (CC BY NC ND 4.0) https://pmc.ncbi.nlm.nih.gov/articles/PMC11100722/ [108]. (b) Snapshot of a simulated foam, from [109] published under Creative Commons license (CC BY NC ND). (c) Sketch of a cross-linked vitrimer, reproduced from [110] with permission, AASS. (d) Particle-laden flow comprising glass beads in glycerol, reprinted with permission from [111] Copyright (2022) by the American Physical Society. (e) Grains flowing down an incline, adapted from [112] published under Creative Commons license (CC BY 4.0)

5. Rheology of complex fluids and soft solids

(a) Hydrogels

Hydrogels are broadly defined as macromolecular matrices made up of polymers, colloids or proteins that are swollen in water. Their viscoelastic behaviour is characterized rheologically by a continuous weak power law for the storage and loss moduli with respect to frequency. This characteristic response is often argued to be indicative of a multi-scale fractal structure [104]. Hydrogel rheology is modulated by several factors, including the type of 'building blocks' (polymer, colloid and protein), the flexibility of the network (rigid and flexible) and the cross-linking mechanism (permanent and physical).

Advances in hydrogel design have been driven by the need for tailored materials across biomedical, materials science and food applications where precise control of viscoelastic properties is essential. A major focus has been on engineering mechanically robust hydrogels through careful tuning of architectural properties, such as network density, cross-linking dynamics and polymer chain mobility. There are intriguing reports that such modification may overcome the traditional trade-off between strength and deformability, making these hydrogels well-suited for load-bearing implants [105]. Other examples include small molecules, which offer easy synthesis and manageable chemical and rheological tuneability, and folded protein hydrogels [106], in which the native structure of biological proteins is conserved, thus incorporating native mechanics and biochemical properties [107]. Furthermore, advancements in dynamic covalent chemistry (figure 4*a*), including Schiff base and Diels–Alder bonds, have produced injectable hydrogels that degrade on-demand [108].

The development of hydrogels has been matched by significant progress in their characterization. A terminal frequency in the frequency spectrum is occasionally seen when the hydrogel cross-links are reversible, and is indicative of the characteristic cross-link unbinding time of the hydrogel. For most hydrogels, however, the characteristic power-law behaviour remains firmly within the accessible frequency range, making such characterization difficult. Nonlinear rheology, imaging and spectroscopy techniques now play a central role in understanding hydrogel structure–property relationships. Time-resolved rheological studies have further elucidated gelation mechanisms, highlighting the role of dynamic bonding in controlling viscosity and stability, crucial for achieving precision in bioprinting [113].

The future of hydrogel rheology will be driven by the structure–property–function relationship. This will require advances in mechanistically informed modelling, with ML-guided design and *in situ* characterization. Linking molecular-scale models [114] to constitutive models aided by ML-guided [98] design could enable custom hydrogels with stress–strain profiles that can be designed *a priori*. This ambitious endeavour will require physics-based, predictive constitutive frameworks that incorporate molecular details and subsequent integration of rich rheological datasets with

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ML algorithms. Another frontier is tracking a hydrogel's internal structure evolution in real time (especially under physiological conditions) and under simultaneous shear, which is inherently technically challenging. Furthermore, standardization of current and novel rheological characterization methods is urgently needed to ensure reproducibility and comparability, particularly for biomedical hydrogels. This is coupled with the persistent assumption of no-slip boundary conditions, which may be a significant source of error in hydrogel rheometry. Multi-modal techniques (e.g. rheo-confocal microscopy, rheo-small-angle X-ray scattering, rheo-small-angle neutron scattering) now allow simultaneous observation of microscale processes (cross-linking/alignment/bond breakage) and structural dynamics but are yet to be fully integrated and are still not generally accessible. Open questions surrounding artefacts and optimal protocols remain largely unexplored; here interdisciplinary collaboration is likely to drive innovation in hydrogel research.

(b) Vitrimers

Traditionally, polymers and polymer rheology are divided into thermosets and thermoplastics. Upon heating (curing), thermosets form a permanent network of covalently bonded repeat units, which is insoluble and cannot be induced to flow by reheating. Thermoplastics comprise long discrete polymer chains that can creep or flow when heated or solvated sufficiently. Vitrimers are a fascinating new class of materials that combine the reprocessibility of thermoplastics with the resilience of permanently cross-linked thermosets. Montarnal *et al.* [110] built on the concepts of supramolecularly cross-linked systems (figure 4*c*) [110], but with the critical difference that bonds were only 'broken-and-reformed' in exchange reactions. This distinction ensures that vitrimers maintain a high degree of solvent and creep resistance. The exchange reactions that determine the relaxation rate typically follow Arrhenius behaviour with a defined activation energy. Montarnal *et al.* [110] reported this as a linear increase in ln (viscosity) with inverse temperature. Stress relaxation tests are also commonly used to describe vitrimeric behaviour as a linear dependence of ln (relaxation time) versus $1/T$. The relaxation rate depends significantly on the cross-linker chemistry and any catalysts present to enable the exchange reaction [115].

The reprocessability of vitrimers is a significant advantage over thermosets such as epoxy resins. Rheology and mechanical testing are needed to test the properties of reprocessed, recycled or self-healing materials. Christensen *et al.* [116] demonstrated that vitrimers based on dynamic diketoenamine bonds could be recycled. They used DMA to test the mechanical properties, as well as shear rheology to determine the activation energy of 49–60 kJ mol^{-1}. At processing temperatures in the range 140–170°C, the characteristic relaxation time varies by a factor of approximately 3, which is a relatively small shift compared to the temperature dependence of relaxation rate for rubbery polymers near their glass transition temperature. The properties of vitrimers lend themselves to applications in adhesion. Vitrimers have also been used to provide a resilient framework to align liquid-crystal elastomers. Here, uniaxial stress testing shows the relationship between liquid-crystal alignment and tensile stress [117]. The combination of recyclability with mechanical stability of vitrimers is of interest for electronics and particularly for the important issue of minimizing electronic waste. Given the drive for sustainable alternatives to single-use plastics, it is hardly surprising that vitrimers have sparked significant interest.

In recent years, the focus of research into these materials has moved towards new chemistries including renewable feedstocks and vitrimer composites. Much of the early work on vitrimers was based on ester-bond exchange chemistry, but other chemistries including modifications to sulfur vulcanization have also been reported. Hanna *et al.* [118] focus on recyclability as a unique distinction of inverse vulcanized rubbers from traditional rubber. They described inverse vulcanized rubbers in which the exchange reactions yield vitrimeric mechanical properties through exchangeable S–S bonds, forming a notable example of vitrimeric nanocomposites [119]. Factors that are relevant to polymer composite rheology, such as the influence of polymer–filler interactions on stress transfer, apply equally to vitrimer composites. Demarteau *et al.* [120] demonstrated vitrimeric behaviour in polydiketoenamines, which are bio-derived, and can have sufficiently high

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T_g to be suitable for automotive applications. Bio-based and bio-renewable vitrimers have also been reported. These materials offer similar opportunities to tune rheological behaviour, but with added benefits of reprocessability. As well as helping to address the 'single-use plastic' problem, there is future scope for upcycling plastic waste into functional materials. There is also considerable parameter space to explore, such as new physical and topological structures made possible by extremely low cross-link densities.

(c) Suspensions and granular materials

The first of two recent major advances in the understanding of suspension rheology (figure 4*d*) [111,121] was the introduction of the $\mu(J)$-rheology [122], which provided a bridge to the large and established literature on dry granular flow. This constitutive model amounts to a simple dimensional analysis and leads to the important result that the ratio of shear-to-normal stresses μ and the solids fraction ϕ are functions only of the viscous number $J = P/\eta\dot{\gamma}$, where η is the liquid phase viscosity, P is the normal stress on the particle phase and $\dot{\gamma}$ is the shear rate. This provides a starting point for characterizing the rheology of all granular suspensions, which, in the presence of gravity, are better described by this innovative approach rather than by a classical fixed volume fraction one. This model has been extended to many classes of suspensions including soft and elongated particles.

This progress builds on the seminal model for dry granular matter (figure 4*e*) [112], the $\mu(I)$-rheology, which is the basis of most current granular material modelling and is validated by diverse experimental data [123]. Here, the inertial number is $I = \dot{\gamma}a/\sqrt{P/\rho}$, where a and ρ are the particle size and density, respectively. Ongoing work is seeking to characterize and resolve the ill-posedness of both the $\mu(I)$- and $\mu(J)$-rheology [124], a critical step before these descriptions can be used to predict the rheology of granular matter in real-world scenarios by continuum modelling. Similarly important to describing granular flows in nature are detailed descriptions of particle segregation and more complex rheological behaviour, such as non-locality [112].

A second paradigm shift has emerged in the modelling of very high volume fraction 'dense' suspensions, particularly in the non-Brownian and non-inertial regime, relevant for particles of around 1 µm in size. Here, an important series of experiments challenged the status quo by demonstrating that shear thickening occurs in suspensions when particles come into close contact and a critical force is exceeded so that the hydrodynamic layer around the particles is penetrated leading to frictional contact. This work guided the development of a now widely accepted constitutive theory in which the non-Newtonian rheology of suspensions of approximately spherical particles is understood based on the proximity to a stress-dependent critical coordination number [125]. A subsequent generalization to this breakthrough provides a steady-state, homogeneous constitutive model in which arbitrary microscopic constraints, toggled on and off by stress, govern the rheology [126], permitting both shear thickening and thinning depending upon how constraints form and release. This new understanding has made possible innovative approaches to rheological control, whereby direct tuning of the particle roughness [127] or direct mechanical manipulation of the microstructure [128] allows precise tailoring of the bulk viscosity. Later developments provided a transient, tensorial form of the constitutive equation in which the microscopic details are encoded in an asymmetric pair distribution function evolving differently in the compressive and extensional directions [129].

These two approaches provide complementary perspectives, respectively, describing the rheology under fixed stress and fixed overall volume fraction. Fully reconciling their predictions, especially in non-ideal materials that have frictional surface contacts with variable coefficient or agglomeration owing to adhesion, requires further work. Further, it has been shown recently that generic granular materials are predisposed to both shear thinning and thickening dependent upon the flow conditions, an apparent paradox that emphasizes the significance of fixed stress versus fixed volume rheometric conditions and adds further to the challenge of obtaining a unified

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description [130]. Resolving these questions is key to reaching a definitive and widely accepted rheological model for granular materials.

Elsewhere, there has been a focus on suspensions of highly non-spherical particles. Fibres are relevant to applications such as paper manufacture and composite material recycling, whereas graphene particles provide a model system for thin, flexible particles with slip boundary conditions. The discovery of graphene in 2004 created a need to understand the behaviour of thin sheet-like particles past which the suspending fluid could slip freely. In shear flow, these particles do not carry out Jeffery orbits like their no-slip counterparts [131] but can hold a steady inclination to the flow direction [132]. The ramifications of this on the rheology of even dilute nanofluid suspensions are complex and still the subject of current research.

(d) Entangled polymeric melts

Polymeric melts have a nonlinear rheology, which is pivotal to industrial polymer processing. Progress has focused on constitutive equations based on the tube model and its extensions [133], which balance predictive accuracy and computational tractability. The tube model has been extended to polydisperse melts and highly deformed chains. Non-equilibrium molecular dynamics (NEMD) simulations and stochastic slip-link models have given physical insight into phenomena such as segmental friction reduction for highly aligned chains, chain tumbling and variable entanglement density [134], resulting in breakthroughs such as the recent Rolie-Double-Poly (RDP) model [135], which extended a simple constitutive equation to full polydispersity. The resulting model has encouraging predictive ability, allowing its use in CFD calculations of polymer processing. For entangled polymeric fluids, long chains are key to understanding polydispersity. Advances in molecular dynamics simulation for longer chains, coupled with detailed scrutiny of the modelled trajectories to obtain evidence to support and refine new physical mechanisms, will bridge the gap to the full molecular weight range relevant to experiments and industrial processing. Modern AI techniques will potentially automate this process and may even propose new interpretations that humans alone are unlikely to locate. Another future direction is to exploit new understanding of polymer entanglement in wider areas of polymer physics. Two such examples, both important for plastics recycling, are flow-induced crystallization of polymers, where the RDP model and recent advances in NEMD [136] have underpinned recent progress [137], and the modelling of entanglements in blends of multiple chemical species and block copolymers.

(e) Wormlike micellar fluids

Wormlike micellar fluids (WLMs) or 'living polymers' are complex fluids ubiquitous in industrial and technological applications, with a broad rheological response encompassing shear-thinning, strain softening-hardening, viscoelasticity, thixotropy, yield stress and banded flows, originating from their internal-structure breakage and reformation [138]. There are two main streams of constitutive modelling here: models based on a microstructural dynamic description of micellar construction–destruction and their interactions, and other models based on a macroscopic structural parameter that links material response with flow strength. Microstructural modelling of WLMs has built on Cates' pioneering modelling paradigm [139] to incorporate two-species kinetics (the Vasquez–Cook–McKinley model), reversible rod linkage (Reactive Rod Model) and much more. Alternatively, structure-parameter-based models include the Bautista–Manero–Puig family of fluids, the Germann–Cook–Beris model that works with a conformation-tensor-dependent structure breakage rate and the soft glassy rheology model, which predicts shear banding under LAOS deformations. Open problems in WLM research include numerical predictions of complex WLM flows [138] and related instabilities, the introduction of micro–macro approaches, the quantitative prediction of nonlinear features such as transients, banding and turbulence, and the derivation of rheological equations of state, which capture non-equilibrium thermodynamics.

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(f) Soft solids and foams

Soft solids are rheologically complex, and gaining an understanding of their behaviour is essential for smarter material use, efficient design and achieving desired properties. They often display nonlinear behaviour and have intricate microstructures and frequently consist of multiple phases. One key model soft solid, the aqueous foam, consists of gas bubbles in a liquid matrix and has a well-defined microstructure dictated by surface tension. Here, interfaces are stabilized by surface-active molecules, and solid foams often take their structure from such fluid precursors, while emulsions have properties closely related to liquid foams.

Soft solid rheology is usually probed using DMA in uniaxial mode (tension or compression) and/or shear loading. In oscillatory tests, the so-called rubbery plateau is the region where the material is soft but still bears its own weight. In this region, polymeric soft solids are susceptible to temperature-induced changes like melting, crystallization, orientation or reorganization phenomena that govern the structure–property relationship [140]. An application of DMA is in plastics recycling, where the aim is to evaluate the quality of the reprocessed material. In addition, in AM, oscillatory tests have been used to assess the printability of soft solids. The mechanical response at large deformations or rates is often needed for engineering applications. For low modulus materials and specifically elastomers, a method which combines the data from rheometry and DMA experiments has been reported where the test data and resulting master curves calibrate a generalized viscoelastic model incorporating a strain-based damage criterion, predicting the high-rate response [141].

A wide range of constitutive laws have been used to capture nonlinearity including nonlinear elasticity, plasticity, viscoelasticity, viscoplasticity and various combinations of these. Rubber-like materials have been studied for several decades with hyperelastic models, based on either phenomenological or microstructural-based models [142]. These have been implemented in finite element codes and are available for designers when simulating applications involving materials, such as tires, robotic actuators, seals and vibration isolation mounts. A common assumption has been that rubbers deform at constant volume. Recently, literature has shown that, in some cases, even though macroscopically the volume remains constant, many polymers exhibit significant local volume changes arising from mobile phases within the rubber [143]. Hyperelastic models developed for rubbers have been adopted elsewhere such as in foods, gels, polymer-based protective coatings and paints. In the latter, rubber elasticity has been used in conjunction with viscoelasticity to capture the more complex behaviour. The Mullins effect concept, which has been developed for predicting damage in rubbers owing to debonding of filler particles in the rubber, has been used to capture hysteresis and softening [144]. For soft materials with large irreversible flow or deformation, plasticity constitutive models originally formulated for metals have also been used [145]. The increasing yield stress with increasing applied strain rate can then be easily modelled through viscoplastic models. These models can include damage mechanics via a time—or load—evolving damage variable so that softening owing to microstructural changes is captured [146].

Owing to their high interfacial area and significant yield stress, foams find applications in oil recovery, soil remediation, firefighting and food. When seeking to model foam rheology, the most important structural parameters are the proportions of each phase and the average bubble size, R. A foam flows when the applied force is great enough to cause bubbles to move past one another in microscopic plastic events [147]. Otherwise, the foam responds elastically. Both the shear modulus and yield stress scale with γ/R, where γ is the surface tension, and decrease monotonically with increasing liquid fraction. Flowing foams are affected by gravity-driven drainage of the liquid from around the bubbles, gas diffusion between bubbles (coarsening, or Ostwald ripening) and rupture or coalescence. Experimentally, much effort has gone into isolating these processes, for example, by performing experiments in microgravity and using gases with large molecules to suppress diffusion. A related question is how the surfactant is moved by the flow, since interfaces that are depleted are more likely to rupture (figure 4*b*) [109]. At the bubble scale, theory is mostly based on two-dimensional dry foams consisting of hexagonal bubbles or three-dimensional wet

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foams of spherical bubbles. Interpolating between these limits, where the bubbles are deformed, is more challenging, as is including the effects of geometric and topological disorder. Numerical approaches at this scale are similarly clustered at the extremes of liquid fraction, either with vertex models or surface evolver [148] in the dry limit, or so-called bubble models [149] in the wet. In the continuum limit, it is natural to treat foams using a Herschel–Bulkley or EVP model [150,151], and the challenge is to relate the yield stress and effective viscosity to the microscopic properties of real foams.

Though several models for soft solids exist in the literature, their availability in commercial software remains limited. If one needs to include any form of evolving damage during loading, then the challenges are even more pronounced. Furthermore, several soft solids are used in applications where mechanical as well as chemical degradations are relevant and chemomechanical constitutive models become necessary. Examples of the latter are foods during processing, *in vivo* drug release and environmental degradation of plastics. Taking into account the complexity of constitutive laws of soft solids on one hand and the large datasets from experimental techniques such as digital image correlation on the other hand, data-driven approaches can complement or completely bypass the need for analytical constitutive laws. Increasing computational power will play an increasing role towards achieving automated modelling for soft solids characterization [152]. Elsewhere, attention is oriented at investigating the rheology of soft solids at the micro- and nanoscale, and in particular biological systems. Very recently, an AFM technique based on photothermal actuation of the cantilever has been reported that enables the measurement of nanoscale viscoelasticity over a frequency range of five orders of magnitude [153].

(g) Food rheology

In a 1946 joint meeting with the Royal Society of Chemistry, the then British Rheologists' Club, discussed the applications of rheology to meat, gelatine and dairy products [154]. Since that joint meeting, we have moved towards an era where high-throughput rheological testing, advanced physico-chemical modification techniques and computational modelling enable precise formulation of food materials with targeted textural and functional properties. Significant challenges persist in extrapolating rheological behaviour measured under controlled laboratory conditions to the complexities of large-scale food manufacturing, particularly for shear-thinning, viscoelastic and gel-like systems. In addition, modern processed foods have been linked to negative health outcomes, such as obesity, diabetes and cardiovascular disease. To counter these issues, food reformulation must address maintaining consumer satisfaction while ensuring that the new products remain marketable and production costs remain low. All these challenges, combined with the fact that foods are among the hardest materials to investigate owing to their heterogeneous multiphase microstructures and complex macroscopic rheological response, have attracted a growing number of rheologists to the field.

Measurement: most published studies use SAOS or rotational rheometry to determine storage and loss moduli as well as viscosity, with fewer using LAOS. Some industries still rely on empirical techniques for assessment of food products, particularly for bread dough. Nonlinear rheology and high-resolution imaging and scattering techniques [155] are useful analytical tools to elucidate the complex flow behaviour and microstructural evolution of food materials under bench-scale and processing conditions. Small-angle light scattering, confocal laser scanning microscopy, nuclear magnetic resonance and calorimetry have improved understanding of the microstructure–rheology relationship in protein- and polysaccharide-enriched matrices [156], fats, emulsions and other microstructured systems. Furthermore, substantial advancements have recently been made in the application of rheology to real-time process monitoring and texture engineering.

Extensional properties are of interest and relevant to food applications, but there are limited methods available to characterize these kinds of materials. This is an area that requires future work, with the common measurement system at present being CaBER, which has severe evaporation issues. Microfluidic methods are well advanced, but measure extremely small sample

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volumes to manage inertia. This is an issue for foods, which are rarely homogeneous, having inclusions which can cause blocking and local microflow perturbations. Water-based materials in foods are susceptible to drying and evaporation, making them time-evolving systems and hence more difficult to study even when the complex microstructure is considered. Solvent traps and humidity control systems are available but are not satisfactory or are exceptionally costly. Improvement of measurement systems to remove artefacts from evolving systems and instrument limitations requires substantial consideration by the rheology community.

Future research prioritizing the development of food-grade, hygienically compliant, in-line rheological sensors that accommodate highly viscous, multi-phase food matrices would bridge the gap between laboratory-scale characterization and industrial-scale implementation. The integration of real-time feedback control systems, which dynamically adjust shear forces, temperatures or flow parameters based on live rheological measurements, represents a key technological frontier in achieving novel, intelligent texture modulation [157].

Processing and formulation: industrial food processing has motivated several rheological studies, for example, extrusion [158], rolling (sheeting) [159] and baking and mixing [160], for investigating the influence of various process variables on the end product. In addition, reformulation for improved properties, sustainability or health is extremely challenging and has been the topic of several studies. These include alternative proteins, emulsions and hydrocolloid systems with high-moisture extrusion playing a pivotal role in structuring plant proteins to mimic the fibrous architecture of muscle tissue. Recent studies [161] have demonstrated that enzymatic pretreatment of plant proteins prior to extrusion enhances their rheological behaviour, improving the final texture of alternative proteins. Reformulation even by a single ingredient (e.g. replacing dairy with plant-based alternatives, reducing salt, fat or sugar) affects the microstructural architecture of foods, the interaction between the components and consequently the whole of the macroscopic rheological response. For example, salt reduction changes the behaviour of charged proteins and carbohydrates affecting the final properties of the desired product [162]. Water activity also changes, resulting in alterations to both hydration of macromolecules and microbiological safety [163]. Development of Pickering emulsions stabilized by cellulose nanocrystals has advanced emulsion stability and functionality in food formulations [164]. The digital transformation of food manufacturing includes AM [165]. This requires stringent control over viscoelasticity and yield stress which is driving co-innovation in formulation design and equipment engineering underscoring the strategic role of rheology.

With sustainability a priority, future research will focus on integrating eco-friendly processing techniques, bio-based stabilizers and energy-efficient manufacturing methods, ensuring that food rheology continues to support innovation in alternative and sustainable foods. Optimizing formulations of plant-based alternatives to meat and dairy products with the aim of enhancing food texture and sensory perception is another area which looks set to occupy food rheologists [166]. Advanced structuring methods, such as enzymatic cross-linking and fermentation, aim to enhance elasticity and mouthfeel. Three-dimensional food printing (and the general field of AM) may further refine anisotropic structures, improving realism in plant-based meats. In addition, hybrid formulations combining plant and microbial proteins offer new textural possibilities. Emulsion stability remains another frontier for food enhancement. Gel emulsions and biopolymer-stabilized systems are being developed to improve shelf stability while maintaining desirable sensory properties.

Human interaction: the oral process is of significant interest; the aim is to use rheology as a tool for predicting consumer perception and especially texture. The oral process includes several stages where food may start as a solid, fragment under the action of the teeth, mix with saliva into a bolus, heat up to body temperature and interact with the oral cavity before it is swallowed. Elastic [81] and viscoplastic [167] rheological models have been employed coupled with damage models to predict food breakdown. There is a significant emphasis on developing products tailored for the aging population suffering from dysphagia with rheology playing a key role during the swallowing process [168]. Gastric processes are attracting significant interest owing to their

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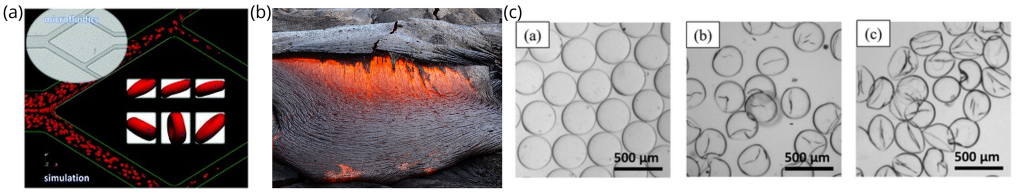


Figure 5. Rheology in nature. (a) Modelling flow of red blood cells (RBCs) in narrow channels using microfluidics and simulation, adapted from [176] published under Creative Commons license (CC BY 3.0). (b) Photograph of a viscous lava flow (adapted from Rufiyaa, CC BY-SA 4.0, via wikimedia commons). (c) A biomimetic model for RBCs, adapted from [177] published under Creative Commons license (CC BY 4.0)

importance for human health. Digesta (food in the stomach) are mixtures of solids and liquids, which are extremely difficult to characterize rheologically. Several experimental studies trying to address this can be found in the literature (e.g. [169]), as well as more recently numerical simulations with predictions of the flow and disintegration of food during digestion. The latter is needed to provide information enabling the development of food products that are beneficial to human health. Most studies assume non-Newtonian fluid models for the stomach contents [170], with fewer studies assuming solid models such as soft solid viscoplasticity in coupled Lagrangian Eulerian models [171] and elastic-plastic or elastic-brittle SPH models [172]. Both gastric and oral processing are complex physiological processes; research is still required for models to become closer to physiology for both *in vitro* and *in silico* methods.

Modelling and AI: predicting and optimizing rheological properties in food systems has led to a range of modelling techniques, including molecular dynamics simulations [157], finite element modelling of complex fluid flows [173] and ML and AI algorithms [101] trained on experimental rheological data to develop understanding of material properties under processing conditions. Modelling has enhanced our understanding of food property–process–structure relationships, which enable real-time simulations of formulation adjustments, reducing reliance on costly trial-and-error approaches. Multi-scale model studies focused on treating foods as particulate composites, suspensions or cellular foams. Various microscopy techniques have been used towards the development of image-based models for predicting the macroscopic response of foods [174]. Such multi-scale modelling approaches enable uncoupling of the geometrical (structure) from the material (rheology) effect on the bulk properties of the product. Future developments include integration of AI-driven predictive models with real-time rheological measurements and physical modelling. This is set to revolutionize food design, improving efficiency and accelerating the development of next-generation food materials. Finally, embedding rheological data within digital twin systems and virtual simulation environments could enable predictive optimization of food processing workflows prior to scale-up trials [175].

Packaging rheology and the interaction of food with surfaces (tribology) are two other areas of importance in the food space that are not covered in this report.

6. Rheology and nature

(a) Magma rheology

Magma rheology is among the most important factors governing volcanic eruptions. Magma, known as lava once above ground (figure 5*b*), is a molten silicate liquid that suspends a variable load of gas bubbles and solid crystals. A packet of magma may start as a pure liquid at the base of the Earth's crust, grow 50 vol.% of crystals during storage in a crustal reservoir, before exsolving 80 vol.% of bubbles during ascent to the Earth's surface. As the composition changes, so does the rheology. Over the last four decades, magma rheologists have described the rheology

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of the silicate liquid, of two-phase suspensions of bubbles and crystals and have begun the work of constraining the three-phase rheology.

Recent research on bubble-bearing magma has resolved a long-standing conundrum by demonstrating that the shape of a bubble, controlled by the capillary number, determines its impact on viscosity [178]. Some earlier workers had found that bubbles increase suspension viscosity, whereas others found the opposite. Similarly, research on crystal-bearing magmas revealed the important role that crystal shape and size distribution play in determining rheology [179]. Consequently, we now have a strong understanding of two-phase magma rheology, which underpins quantitative, predictive models [180]. This rheological insight has supported the development of more sophisticated numerical models of magma flow in the subvolcanic plumbing system, as well as of lava flow over the Earth's surface (e.g. [181]).

The current grand challenge in magma rheology is to develop a general model for three-phase magmas across the wide range of bubble and crystal fractions found in nature. The next generation of models will need to move beyond simple effective-medium approaches and capture the interactions among the suspended phases. This will probably be supported by *in situ* observations of the microphysical behaviour of multi-phase magma via high-temperature X-ray tomography [182]. It is also likely that direct numerical simulation of multi-phase fluid dynamics will become increasingly useful as a tool for *in silico* magma rheometry. It has been shown recently that chemical disequilibrium in magma, arising from the growth of bubble and crystal phases, introduces history dependence to the rheology [183]. Further work is required with magmas, under natural conditions of elevated temperature and pressure, to understand these effects. One of the central motivations for constraining magma rheology is to enable better prediction of hazardous volcanic flows. For some recent eruptions, near real-time measurements of lava rheology have been obtained in the laboratory or even from direct measurements in the field [184]. Future progress towards this important goal will depend on closer collaboration between rheologists, flow modellers and hazard managers.

(b) Ocean rheology

Ocean rheology concerns the effects of natural biopolymers on deformation in three distinct phases: the surface microlayer (SML), the underlying (bulk-phase) water and overlying foam (whitecaps). Regarding the SML, Benjamin Franklin cited Pliny's account that divers in classical times used oil to calm waves, and described his own observations from ships that grease and oil indeed calmed waves. He then showed experimentally that a teaspoonful of olive oil could completely suppress waves on a pond over a surface of 'perhaps half an acre' (approx. $10^4 m^2$). Yet, for over two centuries, physical oceanographers and meteorologists overlooked these observations and continued to make calculations of gas exchange across the sea surface, as if no SML existed. Research aiming to detect ship tracks by satellite-based radar led to publications on the two-dimensional viscoelasticity of the SML using Langmuir troughs and Wilhelmy plates [185]. In addition Carlson [186] sampled water from natural sea-surface slicks, enriched in organic matter, and showed that this water had viscosity higher than non-slick surface water.

Many anecdotal accounts of slimy or 'ropey' water were published, including one describing the water as like egg white [187]. Nonetheless, water movement including turbulence was studied using Navier–Stokes treatments that assume ocean water to be perfectly Newtonian, with viscosity measured at shear rates greater than $1000\,s^{-1}$ while *in situ* values are typically less than $1\,s^{-1}$.

In 1979, a biological oceanographer noticed when snorkelling during a harmful phytoplankton bloom, that underwater bubbles, instead of rising, remained stationary, as if trapped. Inspired by Welsh rheologist Ken Walters, he measured the three-dimensional rheological properties of phytoplankton cultures using a low-shear rheometer [188]. Viscoelasticity is also related to phytoplankton concentration. The spatial variability of ocean rheology is related to aggregation of biopolymers, which are increasingly studied alongside their influence on sinking and rising of organic matter.

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Sea-surface foams (the mystical white horses, or whitecaps) have intrigued seafarers for centuries. They reflect far more radiant light and heat than the sea surface without foam and thus play a crucial role in cooling the Earth. Their longevity and hence percentage cover is controlled by the rheology of algal polymers in the films between constituent bubbles. Monahan [189] studied the effects of wind speed and temperature on foam coverage, while Callaghan *et al.* [190] related their decay time to algal 'surfactants'. The SML variably consists of a more or less broken-up gel and its rheological properties modify ocean-atmosphere fluxes of matter and energy. Thus, it influences the geodynamics of greenhouse gases, heat, moisture, spray and aerosols, related to storm development and the Earth's heat system.

Ocean rheology is progressing in multiple directions. Henderson & Segur [191] concluded that biological viscoelasticity of the SML dissipates the energy over thousands of kilometres of ocean swell, which is responsible for much damage. New measurements of shear-related viscometry correlate mostly positively with phytoplankton and bacterial concentration, but sometimes negatively, suggesting superhydrophobic effects [192]. Partly related to CO_2 sequestration, work is in progress on sinking dynamics of particles at ocean-related scales [193].

(c) Biorheology

Rheology is a powerful tool for probing and manipulating biological systems and is now central to advancements from subcellular components to tissues. The viscoelastic properties of cells, biofilms and extracellular matrices (ECMs) are now recognized as key regulators of biological function, influencing processes such as differentiation, morphogenesis and disease progression.

Recent innovations in rheology-driven cell and particle manipulation have enhanced our ability to control, sort and engineer cells with precision. Microfluidics in particular enables passive, label-free sorting based on size, stiffness or shape, allowing high-throughput separation of cells, vesicles and nanoparticles with clinical relevance [177] (figure 5*c*). Real-time deformability cytometry and optical stretchers provide mechanical phenotyping and active manipulation at single-cell resolution, aiding diagnostics and mechanobiology studies [194]. In parallel, diffusiophoresis, the motion of particles along solute concentration gradients, is a powerful, flow-free method for manipulating colloids and cells, particularly in crowded or fragile biological environments [195]. The application of acoustic and magnetic fields in complex rheological fluids to steer cells and organelles in three-dimensional environments is promising for targeted delivery and organ-on-chip platforms. Advances in three-dimensional bioprinting have leveraged shear-thinning bioinks to precisely deposit cells and enable the construction of tissue models with spatially programmed mechanical cues. The integration of ML-guided flow design and rheologically tunable media is pushing these tools towards adaptive, intelligent manipulation platforms [196]. Collectively, these strategies are transforming bioanalytical workflows and enabling scalable, contactless control in complex biological systems.

A central challenge in biological rheology lies in capturing the dynamic, nonlinear and heterogeneous nature of living systems across scales. Future efforts should prioritize integrating spatio-temporally resolved rheological measurements with omics technologies and live-cell imaging to correlate mechanical changes with biochemical and genetic states. There is also a growing need for standardized, biologically relevant rheological metrics that can be applied across experimental platforms and biological systems. On the application side, the intersection of rheology and mechanobiology offers a promising path towards disease diagnostics, regenerative medicine and targeted therapies in conditions such as cancer and fibrosis. The development of stimuli-responsive materials and feedback-controlled flow systems may enable adaptive rheological control to improve precision in cell sorting, tissue engineering and directing cell fate. Digital twins and ML-guided platforms can enhance predictive modelling of cell responses to mechanical cues [21]. Extending these approaches to study emergent mechanical behaviours in multi-cellular systems and tissues, such as collective migration, jamming and tissue morphogenesis, represents a promising frontier.

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Particle and cell manipulation: the formulation of viscoelastic liquids has recently gained traction for biomedical applications, including cell focusing, separation and single-cell analysis [197]. When particles or cells are suspended in viscoelastic solutions and flow through microfluidic channels, they undergo lateral migration towards equilibrium positions determined by the channel geometry and fluid elasticity. In near-constant viscosity liquids, particles tend to align along the channel centreline, with larger particles doing so more rapidly. Shear-thinning fluids introduce diameter-dependent positioning effects [198], which are less well understood. The ease of preparing polymer solutions relative to complex external set-ups has driven a substantial body of work in this area. Despite strong experimental and numerical evidence describing particle migration, the mathematical complexity of the system has hindered the formulation of predictive design equations, making microfluidic device development heavily reliant on empiricism.

More recent work involves controlling the spatial arrangement of particles, known as viscoelastic 'ordering' [199]. In shear-thinning fluids, particles tend to form equally spaced strings along the centreline, whereas in near-constant viscosity fluids, aggregation is more typical. Beyond its fundamental interest, ordering holds practical relevance for improving single-cell analysis techniques, such as Drop-Seq [200]. This method, which relies on co-encapsulating single cells with functionalized beads in droplets, suffers from low co-encapsulation efficiency owing to uncoordinated particle arrival times. By using viscoelastic ordering to regulate interparticle spacing and synchronize this with droplet formation, researchers have significantly improved encapsulation efficiency, surpassing stochastic limits [201].

Fundamental research into viscoelastic focusing and separation is approaching maturity, with few remaining questions. Chief among them is the elusive formulation of a simple predictive model for focusing in shear-thinning fluids. By contrast, viscoelastic ordering remains an open frontier [202]. Importantly, ordering shows strong potential for enabling high-throughput single-cell technologies. The commercial exploitation of viscoelastic fluids, both for focusing and ordering, remains nascent and offers a promising avenue for future innovation.

Biofilms: biofilms are structured communities of microbes encased within a self-secreted polymeric ECM, comprising exopolysaccharides, proteins, extracellular DNA and other molecules. They play vital roles in biogeochemical cycling but also contribute to infections and serve as hot spots for antimicrobial resistance. A defining characteristic of biofilms is their viscoelasticity, which arises from ECM–microbe and ECM–ECM interactions and is dynamically regulated by biomolecular signalling and environmental cues. Viscoelasticity influences biofilm resilience, molecular diffusivity in ECM and microbial competition in the environment [203]. Recognizing its importance, researchers have integrated tools from imaging, molecular microbiology and viscoelasticity to investigate how ECM composition, structural composition and external flows impact the viscoelastic behaviour, advancing our understanding of biofilm-related infections in humans and plants [204].

On solid substrates, biofilms typically nucleate as hemispherical colonies. Structurally, they resemble colloidal gels or colloid–polymer mixtures, where microbes act as active particles embedded within a self-secreted ECM (dispersion medium). However, dissecting the relative contributions of bacteria and ECM components to biofilm viscoelasticity remains challenging. Molecular biology techniques have been instrumental in resolving these questions. For example, in *Pseudomonas aeruginosa* and their mutant biofilms, their exopolysaccharides Psl and Pel increase stiffness and yield strain, whereas alginate primarily enhances viscosity [205]. By contrast, *Vibrio cholerae* biofilms exhibit a double-network hydrogel behaviour, where interconnected bacterial cells form the primary network [206]. Building on the notion of the hydrogel-like viscoelastic behaviour, recent studies using engineered exopolysaccharide production uncovered a two-step direct correlation of biofilm elasticity with cellular packing fraction [207]. When biofilm colonies are subjected to shear flows, elongated structures known as streamers are formed owing to extrusion of extracellular polymers in the direction of the flow. These streamers exhibit a unique stress-hardening behaviour owing to the entropic elasticity of the eDNA molecules [208]. Collectively, the findings highlight an interplay between structural components (bacterial cells, ECM components and eDNA) in determining biofilm and streamer viscoelasticity.

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The field of biofilm viscoelasticity presents exciting opportunities for innovation, leveraging insights from colloidal physics. While recent experiments have uncovered the relevance of colloidal principles in understanding biofilm viscoelasticity for model microbes, a broader framework capturing viscoelasticity across microbial species and understanding the hierarchical organization of viscoelastic behaviour remains an open challenge.

Red blood cell (RBC) suspensions: blood is one of the most fascinating complex fluids. Its particulate nature and erythrocyte mechanical properties, such as aggregation and deformability, have been extensively researched by the rheology and non-Newtonian fluid dynamics community for many years. While the bulk rheology of blood is well characterized for both animals and humans, developing computationally efficient models that capture the complex effects of blood microstructure remains a significant challenge despite being key for advancing personalized medicine and disease modelling. Advances in microfluidics and particle-based computational methods have offered new insights into the microscale behaviour of blood, highlighting the importance of spatial organization of RBCs and its dependence on geometry, cell depletion and lingering effects, as well as cell aggregation and deformability parameters that are altered in disease.

Recent advances in blood rheology have been extensively reviewed by Beris *et al.* [209], summarizing efforts of the community to develop constitutive models that accurately capture the non-Newtonian features of blood, namely, shear thinning, yield stress, thixotropy and viscoelasticity. Among these developments are new TEVP models capturing rouleaux dynamics, RBC deformation and plasma viscoelasticity, while accurately reproducing pulsatile flow and cell depletion in tube geometries [210]. However, a key challenge in modelling haemodynamics lies in the multiscale nature of the vascular system and associated pathologies; in particular, the heterogeneity implicit in the complex microvascular networks arising from RBC dynamics, interactions with vessel walls and with each other. These microscale effects have been the focus of extensive research, with numerous studies investigating RBC partitioning in single (e.g. [211]) and successive bifurcations [176] (figure 5*a*), as well as idealized network and honeycomb-like structures [212], illustrating how cell depletion and lingering effects shape haematocrit distributions farther downstream. Particle-based models employing lattice Boltzmann, dissipative particle dynamics and immersed boundary methods have successfully captured these effects, albeit mostly in simplified geometries; van Batenburg-Sherwood & Balabani [213] described a method to assimilate experimental RBC velocity and concentration data for bifurcating flows into a continuum numerical modelling framework, while Farutin *et al.* [214] proposed a universal law for blood flow predicting local RBC and fluidity distributions. Eulerian–Eulerian two-phase models have also been employed to replicate velocity and hematocrit distributions in microscale blood flows (e.g. [215]). In efforts to understand the role of pathologies on haemorheology, researchers have studied the impacts of RBC deformability and aggregation on microhaemodynamics and platelet margination, via modelling and experimentation. Sickle cell disease, diabetes and storage of transfusion blood are some areas that have received particular attention. Biomimetic spleen-like flows have been utilized to study RBC mechanics [216], while lab-on-a-chip approaches have been engineered to study bleeding and thrombosis.

Despite substantial advances, the following challenges remain: (i) comprehensive rheological characterization of human samples for constitutive modelling requires substantial volumes of blood. This poses a challenge for reliably and repeatably characterizing 'abnormal' patient samples hindering patient-specific tuning of advanced rheological models; (ii) physiological and pathological processes in the cardiovascular system span multiple spatial and temporal scales. Patient-specific, image-based models of vascular disease typically rely on continuum approaches, while many microscale or molecular mechanisms are often modelled using mechanistic frameworks that generally overlook the cellular nature of blood. There is a need to translate high-resolution cellular-scale simulations into clinically relevant, patient-specific models; (iii) the potential for data-driven methods to predict the spatial organization of RBCs and build fast microstructure-based models of blood flow remains unlocked. For example, Ebrahimi & Bagchi [217] have demonstrated that ML can reproduce haemodynamic behaviour in large-scale

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microvascular networks while reducing computational time compared to fully resolved cellular simulations; (iv) recent progress in blood microfluidics has deepened our knowledge of blood biomechanics at the microscale and revealed new biophysical markers. Attempts to translate these insights into clinical practice through point-of-care diagnostic tools exploiting RBC mechanical properties are emerging, offering promise for early disease detection and personalized monitoring. Integrating these technologies into robust tools to inform clinical decision-making in real time remains an active frontier; and (v) researchers have engineered capsules mimicking RBCs, and various blood substitute products have been developed (e.g. ErythroMer). The challenge is to synthesize artificial blood that fully replicates the complex properties of human blood for clinical use.

Low yield stress biosuspensions: the measurement of low yield stresses (less than 10 Pa) in biosuspensions is challenging owing to their microstructural heterogeneity, particle interactions and time-dependent behaviour. Conventional rheometers struggle with wall slip, particle movement and sample disruption, especially for fibrous or high-volume biomass. Modified protocols, such as roughened surfaces [218], static auger insertion [219] or squeeze flow tests, improve accuracy but lack sensitivity for low yield stress measurements. Recent innovations, such as the slotted plate geometry [220], Hele-Shaw microfluidic extensional flow devices (MEFDs) and non-intrusive ultrasound image velocimetry (UIV), aim to address these gaps, but standardization and sensitivity remain limited. These methods address critical challenges of sensitivity and sample integrity in conventional rheometry. Novel techniques have also expanded measurement versatility for diverse materials and measurement limits. The syringe test offers rapid yield stress estimation by analysing droplet mass during filament breakage, validated for dodecane emulsions, Carbopol gels and kaolin suspensions [221]. In addition, MEFDs enable ultra-low yield stress measurements (less than 1 Pa) through stagnation zone analysis, achieving a 5 mPa detection limit and successfully characterizing human blood yield stress (30–80 mPa) against rheometer data [222]. While these methods show promise for real-time applications, challenges remain in optimizing particle settling effects and pinch-off precision (±20% error for yield stress less than 1 Pa in syringe tests).

Hybrid approaches promise to revolutionize yield stress characterization through synergistic technologies. Ultrasound rheometry, particularly when combined with advanced UIV, offers unprecedented non-invasive capabilities for real-time yield stress monitoring in opaque biological suspensions [223]. The integration of ML with traditional viscometry presents a transformative potential, enabling automated parameter estimation for complex rheological models (Herschel–Bulkley, Bingham plastic) while minimizing the systematic errors prevalent in current methodologies [223,224]. The development of field-deployable microfluidic systems, particularly portable MEFDs enhanced with AI-driven image processing [222,224], could bring laboratory-grade yield stress analyses to point-of-care and industrial settings. Adaptive rheometry represents another paradigm shift, where smart rheometers dynamically optimize testing protocols (e.g. strain rates and deformation modes) in response to real-time feedback from complementary techniques, such as ultrasound tomography [225]. Furthermore, novel actuation methods employing ultrasound-induced vibrations and targeted mechanical impulses detect the change in suspension polymeric network structure. Establishing open-source frameworks for rheological data sharing and ML model development is critical for accelerating progress in biosuspension characterization. Such platforms would facilitate protocol standardization, enable benchmarking of novel techniques and significantly reduce redundant experimental efforts.

7. Rheology and manufacturing

(a) Battery manufacturing

In the manufacture of battery electrodes, a slurry of active materials is coated onto a foil current collector (figure 6*a*) [226]. The microstructure and hence the rheology of the slurry can vary significantly depending on the formulation and mixing process, thus affecting performance in the sub-

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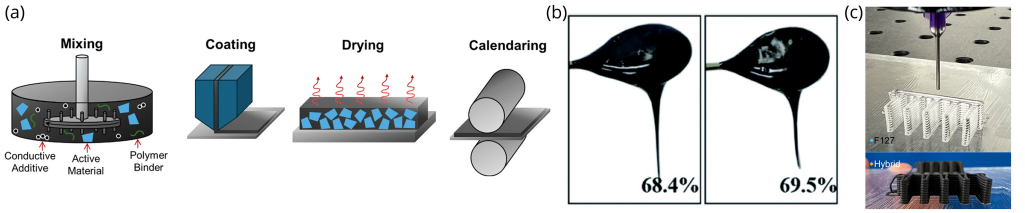


Figure 6. Rheology and manufacturing. (a) Rheological aspects of the battery electrode manufacturing process, adapted from [226] published under Creative Commons license (CC BY 4.0). (b) High solid content cathode slurries, adapted from [227] published under Creative Commons license (CC BY NC NC 3.0). (c) Snapshots of printed hydrogels and advanced materials formulations adapted from [228] published under Creative Commons lisense (CC BY 4.0)

sequent coating process and the properties of the final coating. Therefore, rheology can be used in multiple ways, as quality control for the raw materials and slurry mixing, to extract parameters for modelling of the coating process and crucially to provide a window into the microstructure early in the process to draw out the science underpinning battery manufacturing.

Recent work has mapped the impact of solid content for cathode slurries, identifying a key rheological transition as particle contact increases (figure 6*b*) [227]. Others have linked rheology and electrical properties to show how conductive networks break and reform with shear; notably, cathode rheology is determined by the conductive carbon network, which is not present in water-based anodes, so that the polymeric binder determines the rheology [229]. For difficult-to-process slurries, for example, in high-nickel cathodes, the use of rheology to monitor the gelation process has provided a new method for evaluating stability [230]. Despite this progress, improved measurement techniques and interpretation of slurry properties [226] along with physics-based models [231] are both crucial for further optimization of battery electrode production.

Understanding structure–rheology relationships for electrode slurries is a key challenge. Although the effect of various formulation changes has been mapped out, a systematic understanding of how particle and polymer interactions combine to give structures in the slurry and thus different bulk rheology is lacking. Experimental and modelling approaches must be combined to develop universal relationships robust to different formulations. Opportunities also lie in modelling the electrode coating process. While the coating thickness can be predicted from simple models (e.g. power law), as the formulations become more complex and the processing rates increase, viscoelasticity becomes increasingly important. Finally, we must consider downstream impacts of slurry rheology on cell performance. For example, poor distribution of the conductive additive leaves areas that are not electrically connected, thus reducing cell capacity. There is scope to better use rheology to capture these differences early in the process and adapt to optimize performance.

(b) Extrusion-based additive manufacturing

Extrusion-based AM comprises processes that involve controlled flow through a nozzle followed by layer-by-layer deposition to construct a three-dimensional structure. These processes span a continuum of material complexity, whether that be the usual material extrusion (MatEx) of thermoplastic filament, three-dimensional printing of much softer bio- and food-derived inks or more advanced direct ink writing (DIW) of functional and architected materials. In all cases, the rheological response is central to the elusive question: *what makes a material printable?*

MatEx of polymer melts is the most common AM technique, owing to its low cost, ease of use and broad range of applications. The physics of MatEx is strongly dependent on the flow of entangled polymers at high temperatures followed by cooling and solidification. While original approaches to determining printability relied on material-intensive trial and error, recent efforts have recognized the key role that polymer melt rheology, which has been extensively studied and is well established, plays in answering this question. A detailed review can be found in [232].

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The dynamics inside the heated nozzle are dominated by the shear and temperature-dependent viscosity of the melt. While it is well-known that increased shear-thinning aids extrusion, it is also important to understand the pressure required to extrude the polymer as it transitions from a solid to a molten state, particularly to avoid backflow and filament buckling. A rheological understanding of the extrusion region enables maximum feed rates and minimum temperatures to be recommended. In the standoff region between the nozzle and the print bed, the dynamics are dominated by the residual stresses that build up in the nozzle. This can lead to die swell, which can disrupt the prescribed print dimensions, as well as flow instabilities including sharkskin and melt fracture, which lead to poor surface finish; again, rheology is key to eliminating this behaviour. Ultimately, the dynamics on the print bed are dominated by the interdiffusion and entanglement of the polymer chains across the layer–layer interface before the onset of the glass transition. While contact pressure is a critical determinant of weld strength [233], poor strength has also been linked to residual molecular alignment and partial entanglement at solidification [234]. Thus, understanding the non-isothermal anisotropic reptation dynamics [235] is paramount for defining control parameters. Rheological analyses should be directly leveraged in MatEx, including material selection, parameter optimization and printer design. Foremost, there are opportunities to develop in-line measurements [236] to facilitate real-time monitoring and control. This would greatly benefit the adoption of semi-crystalline polymers, which, while highly desirable, are notoriously difficult to print. There is also a precedent to combine feedstock with fillers and reinforcements to enhance the ultimate mechanical properties; there is a crucial need for a tractable methodology to screen a variety of feedstocks against printability criteria based on rheological characterization. With new capabilities in large format AM, questions arise concerning how the physics of MatEx translates across disparate time and length scales. Finally, linking microstructural features at the polymer scale that first arise in the nozzle and through the deposition and cooling phases to the final mechanical properties that develop in the printed part itself remains a challenge.

Three-dimensional printing of bio- and food-based inks relies on precise formulation and extrusion control. Recent advancements include: optimizing shear-thinning, thixotropy and yield stress to enhance printability, structural integrity and biocompatibility [237]; innovations in hydrogels, nanocellulose, polymer-ceramic composites and stimuli-responsive materials to improve bioink performance and mimic native tissue mechanics [238] and tools such as computational rheology and *in situ* viscosity monitoring to optimize real-time biofabrication. While these advances drive high-resolution, multi-material bioprinting for advanced applications, challenges remain in balancing mechanical strength and biocompatibility for functional, vascularized tissues.

One significant development is the use of hydrocolloid-based formulations for cold extrusion three-dimensional printing. Studies have identified key rheological parameters, such as phase angle and relaxation exponent, which dictate the printability of both biomedical and food-based inks [237], enabling the fabrication of bioprinted scaffolds, as well as personalized food products, with improved textural and structural integrity. Furthermore, the development of polysaccharide-surfactant hybrid gels has led to the creation of gelatin analogs, which mimic gelatin's thermal and mechanical properties while maintaining shear-thinning behaviour, making them suitable for bioprinting [239]. Another breakthrough includes bioinspired composite gels and polymer-ceramic materials tailored for bone and organ-on-a-chip applications, which are designed with enhanced shear-thinning properties and elastic modulus control to improve the stability and functionality of three-dimensional structures [240]. Furthermore, in pharmaceuticals, novel dual-stimuli-sensitive carrageenan-based hydrogels have been developed, exhibiting both temperature and electric field responsiveness [241], which enables controlled drug release and sustained delivery.

Future research should focus on developing bioinks with enhanced biocompatibility, mechanical strength and long-term stability while addressing challenges like batch-to-batch variability and limited material options [242]. Promising directions include the creation of hybrid bioinks combining synthetic polymers for mechanical strength with natural biopolymers for biocompatibility and adaptive bioinks that dynamically adjust viscosity, shear-thinning behaviour and gelation kinetics during extrusion. Food inks need better rheological tuning to preserve texture and

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nutrient integrity while ensuring customized and reproducible food structures. Advancements in post-processing techniques like cross-linking could improve the resolution and functionality of three-dimensional-printed constructs, while smart inks with self-healing and stimuli-responsive properties would allow for improved post-printing durability and controlled release of nutrients or drugs. Interdisciplinary collaboration is key; rheologists must partner with biologists and chefs alike to address challenges such as fabricating vascular networks or meat marbling. Finally, ethical and regulatory frameworks for bioprinting require parallel development.

DIW of advanced materials is widely used for materials beyond polymers, including hydrogels (figure 6*c*) [228], ceramic slurries, metallic pastes, functional materials and two-dimensional materials. These liquid or paste-like 'inks' solidify through evaporation, gelation or other low-temperature methods, rather than typical cooling used in MatEx. Linking the rheology of these advanced materials, which currently lack a universal framework, to their printability through the establishment of structure–properties relationships is a research area in its own right, exemplified by a growing number of reviews and perspectives (e.g. [243]).

Despite diverging approaches and perspectives to the printability concept, the importance of the relationships between rheological properties, processing parameters and the formability of printed structures is agreed. Complex DIW feedstocks can be categorized as TEVP fluids, since they can exhibit a time-varying or thixotropic response, viscoelasticity and plasticity. Rheology has enabled the establishment of relevant DIW protocols and the provision of specific tools to characterize feedstocks: characterization of extensional properties from direct visualization measurements enables expansion of the printability metrics [244]; existing mathematical frameworks (e.g. Fourier-transform rheology [228], SPP [245] and recovery rheology [246]) allow investigation of nonlinear behaviour and transient yielding and their effect on printability and shape fidelity; studies of model yield stress fluids provide a theoretical basis to systematically assess the impact of process parameters [247]. Digital technologies, such as meta-analyses and ML, are also present at the rheology-DIW boundaries.

The challenge is that a single and universally agreed-upon definition of printability is not settled. This is due to multiple factors: (i) the interrelated impact of feedstock properties and process parameters on shape fidelity, (ii) the diversity of DIW systems used, and (iii) the multi-disciplinary context. Nevertheless, printability is an intricate set of metrics that characterize the ability of a material to be extruded (flowability), to restructure within the DIW time scales (recovery) and to create a structurally sound three-dimensional-printed object (material strength, drawability and shape fidelity), for which rheology is key. Promising directions to reach a universal definition will require a collective effort, for example, through relevant dimensionless numbers. Using high-throughput measurements will help build Ashby-type property maps (e.g. as in [228]); combining macroscopic measurements with microscopic observations will enable the study of structure-rheology relationships, and the use of digital technologies with appropriate rheological tools can enhance our capacity to (i) analyse data and establish specific design rules, (ii) exploit direct visualization and image processing, and (iii) automatize *in situ* rheological characterization.

(c) Equipment manufacturers and industrialists

A large proportion of rheology research takes place in an industrial context; rheology is used to inform formulation, processing and product characteristics across a range of structured materials. The state of the art in industrial rheology has evolved significantly over the last three decades. While traditional industrial rheology was the preserve of researchers in high-viscosity systems such as polymer melts and solutions, technical advances in instrumentation, affordability of rheometers and a wider appreciation of the advantages of rheological characterization have meant that industrial rheology has gradually proliferated across diverse communities, including those focusing on emulsions, pharmaceuticals, biological fluids, gels and surfactants.

An important driver has been the widespread availability of stress-controlled rheometers that can also operate in strain-controlled modes [248]. The versatility and increasing affordability of

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such devices have democratized access to sophisticated measurements, bridging the gap between high-specification laboratory rheometers and basic viscometers. At the same time, industrial food research has shifted from theoretical modelling towards experimentally validated approaches, with increasing emphasis on empirically correlating rheological properties with consumer perception through predictive models connecting flow behaviour to sensory attributes.

The evolution of rheology in industry has been highly fragmented in terms of the adoption of new advanced techniques and the continued use of older established ones. In well-resourced research laboratories or large R&D departments with an established research culture, new techniques are being developed. One area of interest is the integration of tribology with rheology; the recognition that both techniques are needed for many formulation applications has spurred the commercial development of tribological attachments for rheometers. Another example is the adoption of powder rheology, through effective standardization and the use of rheo-impedance spectroscopy [249]. Here, direct correlation between passive impedance data and rheological measurements allows material benchmarking and the prediction of material performance, for example, in battery slurries. Nevertheless, traditional rheology remains the workhorse of most industrial laboratories and is gradually extending to higher-value industries, for example, in the pharmaceutical industry where long-standing rheological tests are essential for demonstrating 'structural equivalence' in the development of generic forms of formulations.

A major development across industry has been the application of multi-variate analysis and ML, which have transformed data interpretation, enabling identification of patterns across complex datasets to correlate rheological signatures with product performance. In addition, improved educational resources, largely driven by device manufacturers, have helped overcome rheology's perception as a 'black art', enabling more companies to extract value from their equipment. Our view is that there are numerous protocols that have unrealized potential in industrial rheology. One is zero-shear-rate plateau measurements, as formulated products spend most of their lifetime in low-shear conditions. At the other extreme, narrow-gap rheology for high-shear-rate applications [250] is relevant for printing and extrusion applications in which viscosity variations from storage to processing span multiple orders of magnitude.

Overall, there remains a cultural gap between academic and industrial rheological research, with conventional industrial trial-and-error approaches providing useful, but phenomenological, data, while academic approaches can be well-defined but overly simplistic for applied science. Our view is that a collaborative and virtuous 'best-of-both-worlds' approach is needed for a fundamental understanding of complex formulations. Academic laboratories also have access to unique facilities, such as UV-curing measurements, extensional rheometry, high-shear instruments and integrated optical and structural analysis, which are inaccessible but represent untapped potential for many industrial users. At the same time, in-line rheological measurements during manufacturing in industrial laboratories could revolutionize quality control and provide unique data for fundamental academic analysis. Overall, the industry's future depends on developing skilled rheologists who can extract meaningful data from sophisticated instruments and translate them into product improvements, supported by accessible educational resources that demonstrate the practical value of rheology in development and quality control.

8. Conclusions and perspectives

Rheology continues to play a central role across disciplines ranging from materials science to biology and geophysics, and underpins key industrial sectors including food, healthcare, energy and advanced manufacturing. However, the future development of the field will depend less on its breadth of application and more on its ability to resolve a set of critical questions that are uniquely rheological in nature. In particular, the transition from descriptive characterization towards predictive and design-oriented capability remains incomplete. Below, we summarize what we perceive as four current grand challenges with our recommended strategies for tackling these.

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The first grand challenge focuses on the connection between material structure and rheological response across multiple length and time scales. Despite substantial advances in experimental techniques and modelling approaches, a unified framework that links molecular architecture, mesoscale organization and continuum behaviour under complex flow histories is still lacking. Developments in microrheology, advanced bulk rheometry and multi-scale and multi-physics simulations have significantly improved access to previously inaccessible regimes, yet these approaches often remain compartmentalized. The difficulty lies not only in spanning scales, but in identifying which structural features must be retained to ensure predictive capability without excessive model complexity. This challenge also defines a major opportunity: if resolved, it opens a pathway towards a 'materials-on-demand' paradigm, analogous to the concept of metamaterials in solid mechanics, where flow behaviour could be engineered through precise control of microstructure. This is particularly relevant for complex fluids whose functionality depends sensitively on structure, from hydrogels and suspensions to biological materials. Progress in this area will require the convergence of *in situ* characterization techniques, mechanistically informed constitutive modelling and data frameworks capable of integrating information across experimental modalities and modelling output.

The second grand challenge is the need to connect rheology more closely with fluid dynamics. Many of the phenomena highlighted in this review—elastic instabilities, shear banding, yielding and flow-induced structure formation—are inherently dependent on the flow field and cannot be fully captured through canonical rheometric measurements alone. While recent advances in extensional rheometry, microfluidics and acoustic techniques have expanded the range of accessible deformation conditions, a gap remains between controlled laboratory measurements and the complex, often inhomogeneous and transient flows encountered in real processes. Bridging this gap is not straightforward: even for materials whose rheology is well characterized in simple shear or extension, such as shear-thickening suspensions, unexpected behaviours can emerge in more complex flow configurations. This highlights a fundamental limitation in our current ability to translate constitutive understanding into predictive capability in realistic flows. Addressing this will require a shift in perspective, from measuring intrinsic material properties to understanding the coupled evolution of flow and structure. This includes the development of rheometric techniques capable of spatially and temporally resolved measurements, the establishment of benchmark flow problems, and the integration of rheological models within CFD frameworks capable of handling multi-phase and multi-scale systems. The emerging concept of *rheo-informatics* provides a potential pathway towards this integration but will depend critically on the standardization of protocols and data.

The third grand challenge relates to the increasing use of ML in rheology. This is beginning to reshape how constitutive behaviour is identified and modelled, particularly through approaches that infer model parameters or discover reduced-order representations directly from limited data. Physics- and rheology-informed frameworks have demonstrated clear advantages in accelerated autonomous model selection and parametrization, while methods, such as sparse symbolic regression and universal differential equations, offer new physics-guided and data-driven routes to interpretable and transferable models. The interdependent relationship between mechanistic insight and data-driven modelling positions ML as a tool, which can complement, accelerate and even contribute to enhanced understanding of classical mechanistic constitutive modelling, rather than altogether displacing it. However, key challenges remain, including ensuring generalization across different flow histories, enforcing physical constraints such as frame invariance and extending predictions beyond simple shear-dominated responses.

Finally, while the industrial relevance of rheology is well established, its transformative potential will depend on more clearly defined pathways from laboratory insight to application. This review has identified a range of areas where rheological understanding is critical, including formulation science, AM, biomedical diagnostics and energy systems. In many of these sectors, key bottlenecks arise from the inability to measure or predict rheological behaviour under process-relevant conditions, particularly in the presence of complex flows, evolving microstructure or limited sample volumes. Emerging techniques such as microfluidic rheometry and in-line

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acoustic measurements demonstrate how some of these limitations can be addressed, enabling rapid, non-invasive characterization in realistic environments. Translating these advances into industrial impact will require closer alignment between academic research and application-driven challenges, including development of *in situ* measurement tools, integration of rheological models into digital process frameworks and establishment of shared benchmarks that link rheological properties to performance metrics.

Taken together, these considerations point towards a future in which rheology evolves into a more predictive and integrative discipline, capable of linking molecular design, processing conditions and functional performance. Achieving this will require prioritization and coordination across experimental, theoretical and computational approaches. Progress will depend on developing reduced yet physically grounded descriptions of microstructure, extending rheological characterization into complex flow environments and incorporating data-driven methods in a way that preserves interpretability and generality. As such, the defining challenge for rheology is the integration of its diverse approaches into a coherent framework that is both scientifically rigorous and practically relevant.

This review arose through a collaborative, volunteer-driven effort. The substantial number of co-authors provides a snapshot of several key areas of current and emerging interest within the field, while acknowledging that it is not exhaustive. We hope that the review will serve not only as a reflection of the current state of the art but also as a historical record for future generations of rheologists, just as we have benefited from revisiting the last BSR series of reports (footnote 1 on page 2).

Data accessibility. This article has no additional data.

Declaration of AI use. ChatGPT was used as a writing assistant to improve the drafting of §8. We supplied a detailed list of all the underlying technical arguments we wanted to convey. The AI generated an initial draft, which was subsequently reviewed, edited and validated to ensure it accurately reflected our intended content.

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