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A COMPREHENSIVE REVIEW ON SILICONE OIL: CHEMISTRY, SYNTHESIS, PROPERTIES AND APPLICATIONS

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Abstract- Silicone oil, primarily composed of linear polydimethylsiloxanes (PDMS), represents a unique class of organosilicon polymers with remarkable physicochemical properties that underpin its widespread industrial, biomedical, and technological applications. Its synthesis relies on classical organosilicon chemistry, particularly the Müller–Rochow direct process, followed by hydrolysis, condensation, polymerization, and modification reactions that yield a wide range of derivatives with tailored functionalities.

The unique properties such as a Dielectric fluid, Thermal stability, Buoyancy, Inert nature, Low specific gravity, Viscosity plays as a great role for silicone oil. Hydrophobic property of a silicone oil increase the applications, Thus it is used for polishing agent and also used to make protective coatings. Clinically, silicone oils have transformed vitreoretinal surgery as effective intraocular tamponades. Silicone are effectively used in cosmetic and personal care products. Industrially, they serve as lubricants, hydraulic and heat transfer fluids, antifoaming agents, coating additives, and functional materials in aerospace, electronics, and advanced composites.

This review consolidates progress in the synthesis strategies, structure–property relationships, and multidisciplinary applications of silicone oils, highlighting their versatility and the ongoing innovations driving their future potential.

Keywords- Silicone oil, polydimethylsiloxanes, organosilicon polymers, Dielectric fluid, vitreoretinal surgery

I. INTRODUCTION

A. Background and Historical Overview:

Generally, the term 'silicones' refers to oligomeric or polymeric organic silicon compounds, where silicon atoms are linked together by oxygen so that alternating Si-O-Si bonds are obtained as the backbone. According to IUPAC rules, silicone is known as polyorganosiloxanes.

Silicone oil was first introduced as an internal vitreous substitute agent by Cibis etal in 1962. The United States FDA approved the use of silicone oil as an intraocular tamponade in 1994.

B. Types of Silicone Oil:

1.Polymethyl hydrogen siloxane/ hydrogen silicone oil

Polymethyl hydrogen siloxane oil (C3H9OSi-(CH4OSi)n-CH3H9Si) is mainly colorless, odourless oily liquid used as a waterproof and anti-sticking treatment agent, as a liquid silicone rubber's chain extender, hot forming curing agent, and as cross-linker and improves products elongation at break. Polymethyl hydrogen siloxane oil connected with functional groups like epoxy group and improved the reactivity, absorption behaviour and coupling properties of that particular substance.

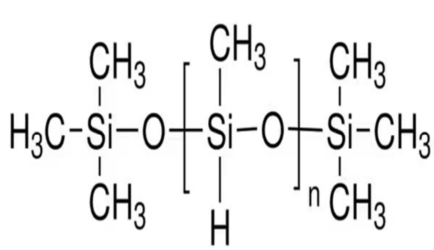


Figure of polymethyl hydrogen siloxane

II. AMINO SILICONE OIL/AMINO SILICONES

Amino silicone oil is applied in textile finishing. Series of amino silicone oil can be obtained satisfactory from wool cotton and chemical fiber. In emulsion form, it provides strong adsorption for the polyester blended yarn, nylon and can tightly combine with active group of fibers. This type of oil plays key role in hair-care cosmetics and shampoos. However, it should be kept away from fire.

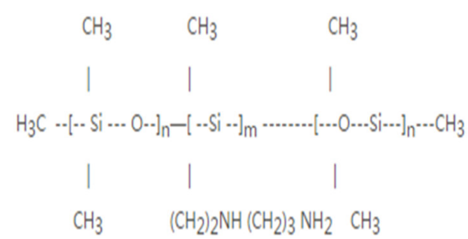


Figure of amino silicone oil

3.Phenyl Methyl silicone oil

Phenyl methyl silicone oil is important kind of safe chemical having special properties like insulation and anti-ozone containing small surface tension and wide working temperature scale from −50 to +250 °C. Phenyl methyl silicone oil can be used as hydraulic liquid and heat carrier at high temperatures .

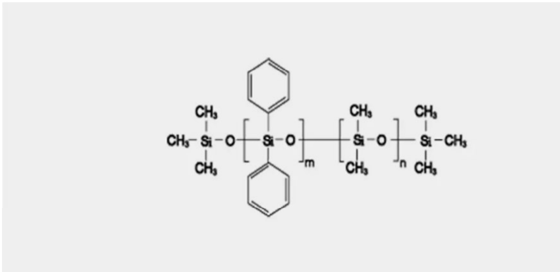
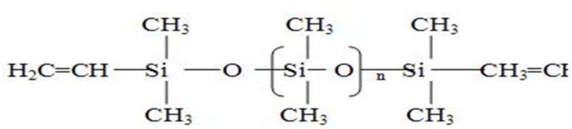


Figure of Phenyl Methyl silicone oil

4.Vinyl silicone oil

Vinyl silicone oil is an excellent and lively intermediate material. Product contains methyl. Silicone oil common performance such as smoothness, limpness, bright, etc. The interesting point of this type of oil is that it reacts easily with organic material such as polyurethane and acrylic acid, etc. Moreover, it is the main material of liquid silicone rubber.



5.Hydroxy Silicone Oil

Hydroxy silicone oil is a transparent liquid commonly used in textile industry having outstanding electric insulator, with high flashing point, large comparison ratio and low surface tension properties. Moreover, it is also used in the anti-adhesion processing of complexity quality paper and as major ingredient of leather smooth ring agent and brightening agent; however, it can be mixed with heated water and alkali substance, etc.

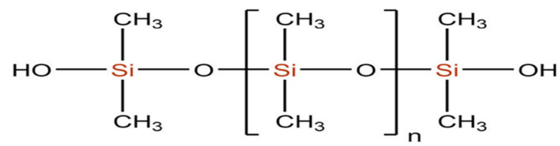


Figure of Hydroxy Silicone Oil

C. Scope and Structure of the Review

This comprehensive review aims to bridge the fundamental chemical and material science of silicone oils (primarily Polydimethylsiloxane, PDMS) with their diverse and critical applications.

The review is structured into the following key sections to provide a coherent and thorough examination:

Section 1 (Chemistry):

This section will detail the basic structure of silicones, focusing on the Si-O-Si backbone, the role of monofunctional and difunctional units, and the nature of traditional functional groups (e.g., Si-H, Si-Vinyl). It will also cover the growing importance of advanced functional silicone oils with incorporated organic groups (e.g., amines, polyethers) used to fine-tune material performance.

Section 2 (Synthesis):

This section will explore the preparation of silicone oil, starting from the formation of chlorosilane precursors via the Direct

Process (Müller-Rochow synthesis). Key polymerization routes will be discussed, followed by a detailed explanation of functionalization techniques, such as the ubiquitous hydrosilylation reaction, which is critical for creating specialty silicone polymers.

Section 3 (Properties):

This section will correlate the unique chemical structure of silicone oil with its exceptional physical characteristics. Key topics will include thermal and oxidative stability, the unique viscosity-temperature relationship, low surface energy, hydrophobicity, and other parameters, including those specific to clinical use (e.g., density, refractive index)

Section 4 (Applications):

This section will present a dual-focus review of applications. It will heavily cover the critical role of silicone oil as a vitreous tamponade in clinical vitreoretinal surgery, including indications and the management of complications like emulsification. It will also review essential industrial and consumer applications, such as lubrication, textile treatment, and high-performance electronic materials.

Section 5 (Conclusion and Future Perspectives):

The final section will summarize the review's main findings and discuss emerging research directions, particularly the development of more stable and less-toxic clinical materials, and the advancement of sustainable, end-of-life degradable functional silicones.

2.Chemistry of Silicone oil

Silicone oils are synthetic polymers composed of repetitive Si-O units, specifically referred to as polydimethylsiloxane (PDMS). These oils exhibit a linear relationship between their molecular weight and the dynamic viscosity (η), wherein both parameters increase with the length of the PDMS chains. It has been observed that higher viscosity is associated with increased resistance of SO to emulsification in vitro, but also with more difficulty intraoperative handling of the substance. Ensuring the purification of PDMS is also vital in obtaining a stable and non-toxic SO that minimizes adverse events. Finding a solution to this remains an ongoing topic of research.

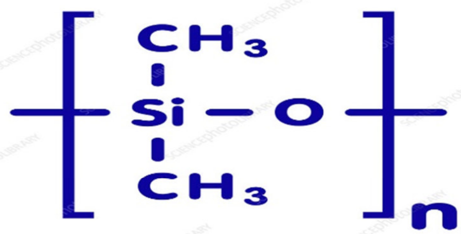
Silicone oil is a term generally used to describe a group of hydrophobic polymeric and monomeric compounds constituted of silicon-oxygen bonds and named organosiloxane. Because of their viscosity and their ability to repel water, they are referred to as oils.

Silicone oils are constituted of a linear chain of siloxane repeating units (–Si–O) and a variety of side chains (radical side groups). Those used in ophthalmology have hydrocarbon radicals as radical side groups (e.g., methyl, phenyl, vinyl, and trifluoropropyl groups). These composts are attached to the silicon atom and it is possible to have many different combinations. Therefore, one silicon atom can bond two radical groups of the same type (e.g., dimethyl-siloxane) or two different groups (e.g., phenyl-methyl-siloxane).

The major differences among silicone oils depend on the molecular weight (MW), on the length of the linear chain, and on the chemical structure of radical side groups, radical end termination of the polymer chains, and the size distribution of the chain. Thus, each type of silicone oil has specific chemical and physical characteristics.

The viscosity of different types of silicone oil, which is expressed in centistokes (1 cs = 10−6 m2/s), arises from the molecular weight and from the length of the polymers: increasing a silicone oil's molecular weight results in an increased polymer chain length and consequently an increase in its viscosity. Silicone oils currently used have a viscosity ranging from 1.000 (MW 37 kDa) to 5.000 cs (MW 65 kDa).

The general formula of silicone oil, specifically polydimethylsiloxane [PDMS] is [-Si(CH3)2O-]n. This formula represents a linear polymer where a silicon atom is bonded to two methyl (CH3) groups and an oxygen atom, which forms a chain with other similar units.



General Formula of Silicone Oil

The 'R' groups can be varied, leading to different types of silicones. For the most common silicone oil, the 'R' groups are methyl (CH3) groups. The 'n' in the formula indicates the degree of polymerization, which determines the chain length and, consequently, the oil's viscosity.

Silicone polymers originate from sand converted to silicon metal and then, via the Direct Process, to chlorosilanes (e.g.,Me2SiCl2, Me3SiCl, MeHSiCl2). The details of these industrial processes are beyond the scope of this paper but have been extensively reviewed. Although the monomers used to prepare silicone polymers are highly functional, there are only a few functional groups that remain in commercial polymer products: Si-H, Si-Vinyl (Si–CH=CH2), and SiOH. Silanols (HOSiR3) are typically found at chain ends of PDMS polymers (PDMS = polydimethylsiloxane) (Me2SiO)n, where they mostly serve as nucleophiles that react with small silanes for moisture cure elastomers (RTV – room temperature vulcanization). The most useful functional group for synthetic chemists is the Si-H group, monomers containing this group (Me2HSiCl, MeHSiCl2) are produced as by-products in the Direct Process in excess to needs of the silicone industry. Si–H bonds are much weaker than C–H bonds. Furthermore, unlike alkanes silanes are hydrides, and the silicon atom is sterically very accessible, so both kinetics and thermodynamics favor reactions, particularly under (aqueous) base or in the presence of silaphilic nucleophiles that convert Si–H to much stronger Si–O bonds. The reaction with aqueous base can be violent, and leads to production of flammable hydrogen gas (note that, under controlled conditions, this process is used for creating elastomeric silicone foams).

III. SYNTHESIS OF SILICONE OIL

A few fundamental reactions are of major importance and characteristic of organo-silicone chemistry, in this case mainly for the production of dimethyl fluids.

Firstly, methylchlorosilanes, which economically represent by far the most important group, are produced according to Muller-Rochow synthesis. The desired product, dimethyldichlorosilane, is obtained according to the equation and method shown in below Figure, where the basic materials, silicon and gaseous methylchloride are converted by means of a copper catalyst, usually in a gas-solid reaction at about 260-320*C.

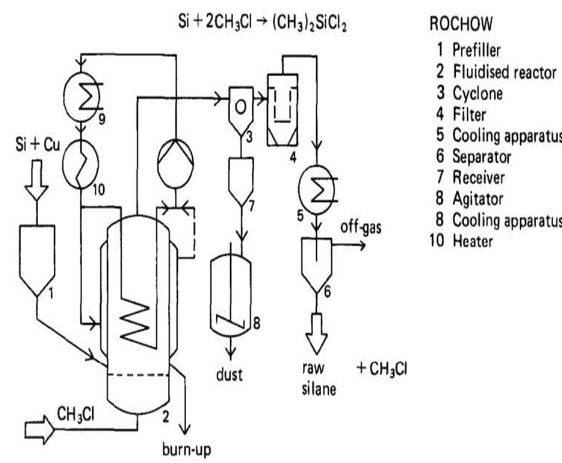


Figure: Gas/Solid catalyst reaction

Hydrolysis or methanolysis of the corresponding organ chlorosilanes followed by condensation are consecutive steps of the silane synthesis. The acid chloride of the silicic acid or their organic derivatives reacts with H20 or methanol.

The reactions are described for dimethyl dichlorosilanes in below Figure , which also shows the subsequent condensation reaction, ie transformation of the silanol groups, obtained by hydrolysis, into higher molecular siloxanes by eliminating water. A problem is the considerable quantity of HCl liberated by the hydrolysis reaction. Methanolysis therefore represents a more economical and an ecologically more favourable procedure as the chlorine can be recycled as methylchloride.

Hydrolysis $(CH_3)_2SiCl_2 + 2H_2O \rightarrow (CH_3)_2Si(OH)_2 + 2HCl$

Condensation $n(CH_3)_2Si(OH)_2 \rightarrow HO{-}[(CH_3)_2SiO]_n{-}H + (n-1)\,H_2O$

Direct synthesis followed by methanolysis:

$$nSi + 2nCH_3Cl \rightarrow n(CH_3)_2SiCl_2$$

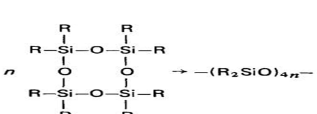
$$n(H_3C)_2SiCl_2 + 2nCH_3OH \rightarrow mHO{-}[(CH_3)_2SiO]_x{-}H + 2nCH_3Cl + (n-m)\,H_2O$$

$$m \cdot x = n$$

$$nSi + 2nCH_3OH \rightarrow mHO{-}[(CH_3)_2SiO]_x{-}H + (n-m)H_2O \quad (6)$$

Figure : Hydrolysis and methanolysis reaction and condensation

Another important type of reaction is the polymerisation reaction i.e. the conversion of siloxane rings free from hydroxyl groups into higher molecular linear polysiloxanes.



The equilibration reaction is of major importance in the preparation of silicone fluids. The aim of this reaction is to homogenise a non-homogeneous siloxane mixture of varying molecular weight distribution by means of catalysis in such a way that the final product exhibits a Gaussian molecular weight distribution. This reaction is mainly used for the production of silicone fluids in order to obtain a desired uniform distribution of the m-units and thus to obtain a specific chain-length and so the required viscosity range. These reactions represent the most important chemical procedures for the production of standard silicone fluids, ie polymethylsiloxanes endblocked by the corresponding m-units. Phenylsilicone fluids and glycol-modified fluids are made using different reactions.

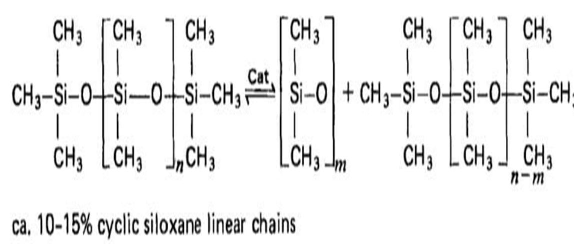


Figure: Equilibration reaction

Another reaction is direct synthesis using silicon and chlorobenzene or the substitution of SiH containing silanes with chlorobenzene, including consecutive hydrolysis reaction of the resultant phenyl chlorosilanes .

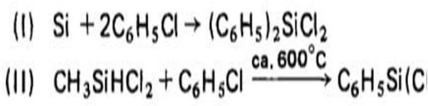
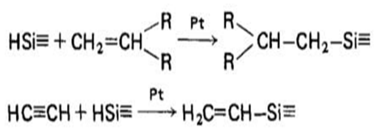


Figure: Direct synthesis

Another is the hydrosilylation reaction, which is the addition of mostly w-terminated olefinic molecules to the Si-H unit usually by means of noble metal catalysis.



Finally, we have the transesterification of alkoxysilyl groups by siloxanes containing silanol endgroups or the insertion reaction of cyclic siloxanes into an alkoxysilyl group.

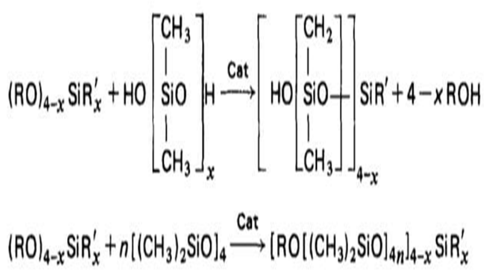


Figure: Transesterification

IV. PROPERTIES OF SILICONE OIL

A) Specific Gravity (SG) : Specific Gravity is very key property of silicone oil. This explains why an intraocular tamponade sinks or floats in aqueous humor. Any substances with an Specific gravity of 1 are neutrally buoyant in water, those with Specific gravity greater than 1 are denser than water and so will sink in it, and those with an Specific gravity of less than 1 are less dense than water and so will float. The specific gravity of aqueous humor and vitreous humor is a little higher than that of water (SD 1.00). Since the specific gravity of silicone oils in comparison is a little lower (0.968), they float in vitreous cavity.

B) Buoyancy : An intraocular bubble of tamponade agent is acted upon by two opposing forces: buoyancy (upward force) and the gravity on the bubble (downward force). Archimedes' principle indicates that the upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially submerged, is equal to the weight of the fluid that the body displaces. Archimedes' principle is a fundamental physics law of fluid mechanics. Regarding the vitreous cavity, the result is the force with which the bubble presses against the retina. For silicone oil, the "pressing" force is relatively small, as the specific gravity is close to that of aqueous humor. The force is greatest with air or gas, as thespecific gravity is very low at 0.001.

C) Interfacial Tension : When two immiscible agents are used together (e.g., silicone oil and aqueous humor), the interaction that occurs at the surface of these substances involved is named interfacial tension. Interfacial tension is a physical rating of the difference between the intermolecular force of the two liquids and it is responsible for the shape of liquid bubbles. Therefore, a substance with a high interfacial tension will have a greater tendency to stay as one large bubble without dispersion into small bubbles. Gas or air has the highest interfacial tension against water (around 80 mN/m), whereas perfluorocarbon liquids (PFCLs) and silicone oils have a lower interfacial tension, around 40–45 mN/m and 35 mN/m, respectively.

D) Viscosity : The viscosity is the major physical property of a fluid which measures its resistance to gradual deformation by shear stress. The tendency of a substance to emulsify and disperse into droplets over time is also dependent on its viscosity. The less viscous a substance, the lower the energy that is required to disperse a large bubble of the substance into small droplets. Silicone oils are there in various viscosity ie. 5 cps (centispoke) to 5000cps (censtispoke). This range of viscosity makes silicone oil to use in large spectrum . Low viscous silicone oil is effectively used in medical applicarion while higher viscous silicone are used in industrial application.

E) Flash Point : Flash Point is another major Property of silicone oil. A flash point is defined as the lowest temperature at which the vapors of a volatile material can ignite. Meaning, that if a liquid is exposed to an external heat source, such as a spark or flame- the vapor released is capable of forming an ignitable vapor or air mixture. Usually silicone oil have higher flash point except low cps oil . High flash point makes silicone oil to use as Heat Transfer Fluid.

F) Inert Nature : Silicone oil have very inert nature. It does not have any toxic effect. It does not react with any other material.

V. APPLICATION OF SILICONE OIL:

A) Clinical Application: The history of silicone oil in ophthalmic surgery is very short in comparison with gases. In the USA, in fact, silicone oil as intraocular tamponade has been approved by the Federal Drug Administration only in 1996. Since that date its use has increased very fast. The first indications were complicated retinal detachment due to PVR or viral retinitis, giant retinal tears, trauma, and severe proliferative diabetic retinopathy . New possible indications are now retinal detachment due to macular hole in highly myopic eye , chronic and persistent macular hole, colobomatous retinal detachment , and chronic uveitis with hypotony . In summary, every time a long-term tamponade is required. Silicone oil has in fact the important advantage of determining a long support until the recovery of the retina has occurred. In case of retinal detachment, we usually perform a silicone oil removal after 3–6 months because we believe this time is sufficient for the recovery of the eye with minimal risk for the development of a PVR.

Silicone Oil emulsification is a well-known complication characterized by the fragmentation of Silicone Oil into small droplets, which can migrate and damage various ocular structures.Several studies have reported cases of emulsification occurring either during Silicone Oil tamponade or after Silicone Oil removal. The onset of emulsification of Silicone Oil in vivo has been reported with an average of 13.2 ± 4.8 months(ranging from 5 to 24 months).

B) Lubrication : Silicone oil are greatly used for lubrication in industrial field. Silicone oil is used as a lubricant for metal, plastic, and rubber components in applications like automotive parts, hinges, chains, and gears, and in specialized areas such as electronics, food processing, and medical procedures. It is also used in consumer products like polishes and cosmetics to provide a protective, water-repellent film.

C) Textiles : Aminoalkylsilicones spread across cotton and other fibers and convey 'softness' to fabrics. Silicone oil have been used in textile industry for softness of fabric ad cotton.

D) Agriculture : Silicone oil also have lot of application in agriculture. The use of high density cationic charge is a common strategy for killing bacteria on surfaces. Silicone quaternary ammonium surfactants are often used to size fabrics to convey this antibacterial activity. Polyether-modified trisiloxanes are widely used as adjuvants in agriculture where they facilitate spreading of pesticides/herbicides on leaf surfaces.Silicone polyethers aid in controlling bubble density and size to structure polyurethane foams, such as those used in furniture.Ironically, silicones are also excellent defoamers and, because of their safety with humans, are used in a myriad of industries,including the food industry, pulp and paper, etc.

E) **Electronics/ Materials** : Silicone oils only start to thermally degrade – in air, or the presence of oxygen near 325*C; phenylsilicones have even higher thermal stability. Silicones are used, for example, as domes for LEDs or in the O-rings for UV lamps because of their much higher resistance to thermal and photodegradation, including oxidation, than traditional organic polymers.

F) **Biomaterials** : The very large free volume of silicone polymers leads to very high gas permeability5 which, in turn, leads to utilization in applications like contact lenses that must allow oxygen to pass to the cornea through the lens.

G) **Heat Transfer Fluid (HTF)** : Silicone oil have high flash point (usually more than 280 degrees C), so these property of silicone oil leads to use as a heat transfer fluid in various oil and gas industry, thermal powerplant,etc.

H) **Emulsification** : Silicone oil is effectively used for making silicone emulsions, which have various application. Emulsion are used for shining automobile parts and other.

I) **Coating :** Silicone oil is used as coating on material to prevent from rust, moisture,etc. Silicone oil are coared around heritage site to prevent damage due to moisture.

J) **Other Applications :** Jiang, X., et al. modifed vinyl silicone oil (VSO) with polyacrylate latex by emulsion polymerization. Shell-core structure was observed on transmission electron microscopy. High softening efect of VSO is proved by the application of the latex as a binder pigment printing on textile. These printed fabrics show synthesized shell-core latex used as binder textile [1]. As we have mentioned the application of silicone oil earlier, here giving much more information about the table, Tween@ 80 helps in the protein formation with the silicone oil, giving protein aggregation and particle formation [1]. Silicone oil also has the potentiality in the microwave atmospheric plasma jet, used to fabricate hydrophobic glass[2-4].

enrollment in local colleges, 2005

Sr no.	Applications	Reference
1	Used as a protein formations	[1]
2	Used in microwave atmospheric plasma jets	[2]
3	Provide a relief stress pattern to the flms	[3]
4	Widely used as a lubricant in syringes to ensure a smooth gliding behaviour	[4-7]
5	Widely applied in industrial products	[8]
6	Play a key and primarily in hydraulic fuids role	[9]
7	Excellent improvement showing in wettability and mechanical strength	[9]
8	For long and high temperature they show excellent mechanical stability	[10]
9	Widely used in high-performance coatings	[10]
10	Shows adhesion strength and hydrophobicity	[10]
11	Employed in the form of emulsion	[11]
12	Used for high-quality shampoos and conditioners	[11]
13	Used for dopamine as a coating materials	[12]
14	Applied as a spinner onto the pretreated sample surface	[13]
15	Reducing the coating porosity and increased the water content angle	[14]
16	Reducing coefcient friction	[15]
17	Good solvent for non-polar compounds	[16]
18	Decreasing the surface tension	[16]
19	Provide a base for mineral oils	[17]
20	Benefcial for moisture preservation	[18]

Silicone oil provides a relief stress pattern to films; Ni films deposited on silicone oil surfaces by thermal evaporation method have been studied systematically [5]. Nowadays, silicone oil is widely used as a lubricant in syringes to ensure a smooth gliding behavior especially in the field of pharmaceutical [6-8]. It is widely applied in industrial products like (ARISTO) silicone spray, industrial silicone lubricant, silicone oil polymerized siloxanes, type 200 fluid silicone oil, etc. [9]. It plays a key role in hydraulic fluids such as universal hydraulic fluid, silicone brake fluids, hydraulic jack oil, etc. [10]. It also shows excellent improvement in wettability and mechanical strength [11], and for high-temperature silicone oil it shows excellent mechanical stability [12]. It is also used in high-performance coating like helmar H400 silicone oil and silicone gun oil-35 which give a high-quality fnish to gun and accessories repelling moisture dirt and fngerprints [13]. It shows long-term adhesion strength and hydrophobicity [14,15]. Silicone oil also employed in the form of emulsions in personal care products due to their inert nature such as antifoam FDP antifoam emulsion, Loctite 770-NC frekote, etc. [11,16]. Silicone oil also provides a high-quality shampoos and conditioners such as silicone hair treatment oil, max wonder GRO hair and body moisturizer and silicone proteina de perla shampoos, etc. [11]. Silicone oil also used as a dopamine for coating materials [12]. It also applied as a spinner onto the pretreated sample surface [14]. Also reducing the coating porosity and increased the water content angle [14]. Silicone oil also reducing coefficient friction, good solvent for non-polar compound decrease the surface tension like BT-3393 types of silicone oil used for hair coloring, fluorine silicone oil widely used in textile, paper and polymer, etc. [15,16]. Silicone oil provides a base for mineral oil such as super lube direct food contact oil,KY-2500 silicone-based oil, antifoam agents and clear white mineral oil–liquid paraffin use for external use only[17]. Silicone oil is also beneficial for moisture preservation like silicone free skin care moisturizer, aveeno active natural smart essential moisturizer and salon style moisturizer, etc. [18].

VI. CONCLUSION AND FUTURE PERSPECTIVES :

In this review, we focus on chemistry, synthesis, property and applications of silicone oil. Silicone polymers are deeply integrated in the lives of many of us, both in our personal contact with them and in the many products that benefit from their use. This review focuses on wide application of silicone oil which are used by us in day to day life. This review also helps to understand sustanibilty of silicone oil.

There are lot of research opportunity are there, such as

- Development of less-toxic, more stable long-term vitreous substitutes for clinical use.
- Research into methods to improve sustainability, including creating new functional silicones that incorporate degradability at end-of-life.
- The continuing search for new functionality in silicone chemistry.
- New synthesis method which helps to synthesize fast and non toxic effect.
- New various Applications.

VII. ACKNOWLEDGMENT

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VIII. DECLARATION

Conflict of interest: The authors declare no conflict of interest.

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