Nanoparticle-based Treatment Strategies for Toxoplasmosis

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Abstract

Toxoplasmosis is an infectious disease that stems from the intracellular parasite *Toxoplasma gondii* which infects approximately a third of worldwide individuals. The standard treatments of toxoplasmosis face restrictions because of low pharmaceutical availability alongside emerging drug resistance and side effects throughout the body. Nanotechnology has proven to be a promising approach for developing new therapeutic strategies because it enhances drug delivery methods while improving treatment effectiveness and targeted *Toxoplasma gondii* action. A general exploration of nanotechnology applications against *Toxoplasma gondii* infection forms the core content of this chapter. Research has demonstrated that nanoparticles represent an effective solution to overcome shortcomings linked with traditional anti-toxoplasmosis drug treatments. Scientific research has produced different nanoformulations like liposomes with polymeric nanoparticles and solid lipid nanoparticles as well as nanomicelles to deliver anti-parasitic agents effectively. The advantages of nanocarriers include drug delivery systems that extend medication availability while safeguarding drug substances from breakdown and support parasite-targeted drug delivery to infected cells. Surface modifications of nanoparticles make it possible to enable precise ligand-receptor interactions that direct drugs specifically to parasites for better treatment results with fewer unknown effects on other targets. Current research has produced nanotechnology-based diagnostic tools using nanoparticles which detect *Toxoplasma gondii* antigens or DNA at sensitive levels and rapid speeds to help make early diagnoses and prompt medical actions. The practical application of nanocarriers in therapy requires more research toward improving nanocarrier designs drug loading optimization and long-term safety evaluation. Nanotechnology demonstrates great potential to change how toxoplasmosis gets managed through new diagnostic and therapeutic methods. Nanotechnology partnerships with anti-toxoplasmosis treatments create promising developments in creating better and safer treatments to combat *Toxoplasma gondii* infection.

Keywords: Nanotechnology, *Toxoplasma gondii*, Drug delivery, Nanoparticles, Nanoformulations, Targeted therapy, Anti-parasitic agents, Nanocarriers, Toxoplasmosis treatment

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Introduction

The protozoan parasitic organism *Toxoplasma gondii* causes infection in most endotherm animals including humans which leads to the disease known as toxoplasmosis. When *T. gondii* parasites reach their final host like cats they complete their apicomplexan protist life cycle in the animal's small intestine. The production of oocysts that originate from sexual reproduction brings about this endpoint (Carossino et al., 2021). Oocysts produced by toxoplasmosis-infected cats show lengths between 11 to 13 µm when they exit through defecations carrying sporulation-free bodies. After sporulation completes oocysts release sporozoites into the body when a transitional host ingests them. Upon consumption, tachyzoite develops within infected cells located in lymph nodes and intestines through a fast-dividing asexual reproduction pathway (Daher et al., 2021). Acute toxoplasmosis develops due to tachyzoite spread throughout the body while their fast duplication and resulting damage to host cells results in clinical signs that range from mild to severe based on immunological state and which organs are involved (Carossino et al., 2021). Next follows tissue cyst development through bradyzoite stage growth which makes slow duplicates. These tissue cysts which develop in muscle tissue along with the liver and brain maintain their presence throughout the entire intermediate host lifespan. After consumption by animals especially cats bradyzoites release from tissue cysts and reproduce asexually inside intestinal epithelial cells while simultaneously conducting sexual reproduction to create oocysts (Daher et al., 2021). When tissue cysts find their way into a different intermediate host through ingestion both dissemination and tachyzoite replication become the defining features of the acute life cycle phase. The transmission of Tachyzoites occurs vertically to fetus tissue when maternal infection develops during pregnancy. The clinical outcomes become severe due to a dependency system between infection duration and host species type (Ramsugit et al., 2016). The parasitic organism *Toxoplasma gondii* maintains its status as one of the most successful parasites because it possesses the ability to use any endotherm animal as a paratenic host. Human beings repeatedly experience exposure to *T. gondii* based on current population projections which indicate exposure

affects approximately 30–35% of people (Robert-Gangneux & Dardé, 2012). Exposure frequencies in populations are highly dependent on daily activities and dietary behaviour patterns which affect between 10% to 80% of people (Flegr et al., 2014; Jones et al., 2014).

A complete *T. gondii* life cycle needs intermediate hosts to work alongside definitive hosts to continue its progression cycle. *T. gondii* life cycle (Figure 1) requires intermediate and definitive hosts to execute its sexual and asexual replication phase. The sexual advancement within its life cycle occurs exclusively in felid digestive systems that serve as definitive hosts. *T. gondii* starts to infect intermediate hosts that contain warm-blooded animals through oocysts found in contaminated foods or drinks that are ingested. That identical life stage originated from faecally transmitted oocysts previously excreted by cats (Jg, 2004). The acute phase of infection begins shortly after infection when tachyzoites reproduce rapidly thus resulting in a massive increase in their numbers before transitioning into bradyzoites as time passes. Over time the parasite develops into tissue cysts which invade the cells of host organisms. Immuno-compromised patients face a lethal risk when toxoplasmosis infection occurs because bradyzoites transform into tachyzoites. The intermediate hosts alongside definitive hosts play a crucial role in toxoplasmosis transmission by releasing tachyzoites and tissue cysts (Mose et al., 2020).

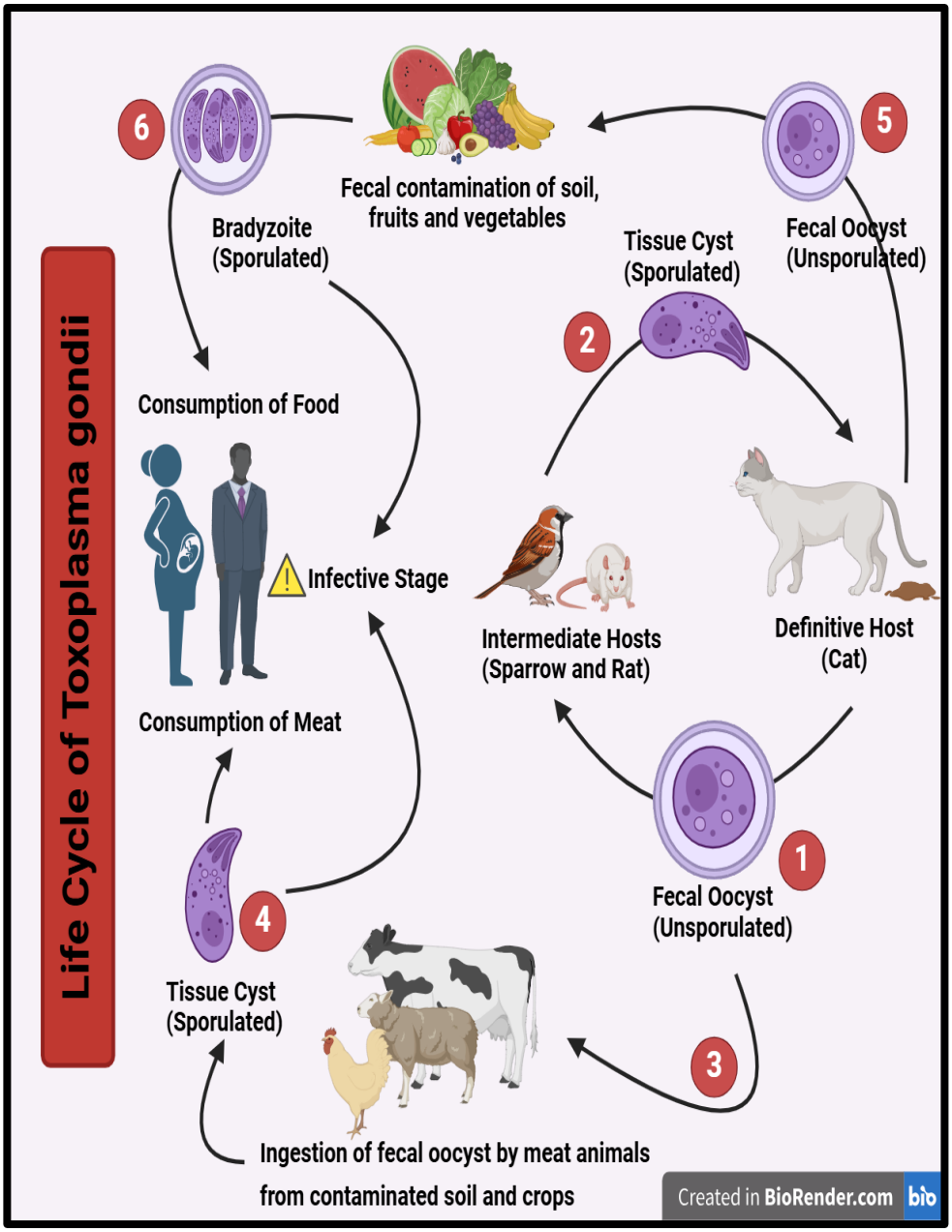

Fig. 1: Life cycle of *Toxoplasma gondii*

Stages of *T. gondii* Infection and Development in Cats

Bradyzoites exit tissue cysts to invade enterocytes within cat intestines where they transform into merozoites as depicted in Figure 2. The sexual life cycle begins when Merozoites evolve into macrogametes (female cells) or bi-flagellated microgametes (male cells). The fusion of specialized sex cells creates a single zygote. Following zygote production cats release oocysts into the environment through their waste. The zygote evolves into sporozoites capable of infection through the sporulation process. The GI tract of new hosts receives sporozoites that swiftly

become tachyzoites. Under stressful situations, the parasite transforms asexual tachyzoites into bradyzoites that become resident inside tissue cysts. Scientists have yet to uncover the regulatory systems which control *T. gondii* developmental differentiation (Aguirre et al., 2019).

Prevalence of *T. gondii* Infections in Humans

The parasitic disease Toxoplasmosis exists worldwide as a zoonosis. Medical specialists first identified *T. gondii* infection in humans during the late 1930s (Halim et al., 2021). During 1939 Sabin demonstrated that isolated Toxoplasma particles from human subjects belonged to the same species as those extracted from animals. Research into *T. gondii's* presence and prevalence worldwide became possible in 1948 through the development of the methylene blue dye test by Sabin and Feldman. Since its discovery, the parasite has infected about one-third of all human individuals living worldwide (Mose et al., 2020). The range of seroprevalence estimates for human populations varies widely across different countries as well as across different geographical locations inside each country and among different ethnic groups located in the same region (Vial et al., 2022). Research from multiple human adult populations spanning the last thirty years showed antibody presence in *T. gondii* cases ranging between 0 and 100 % in the test subjects (Lopes et al., 2021).

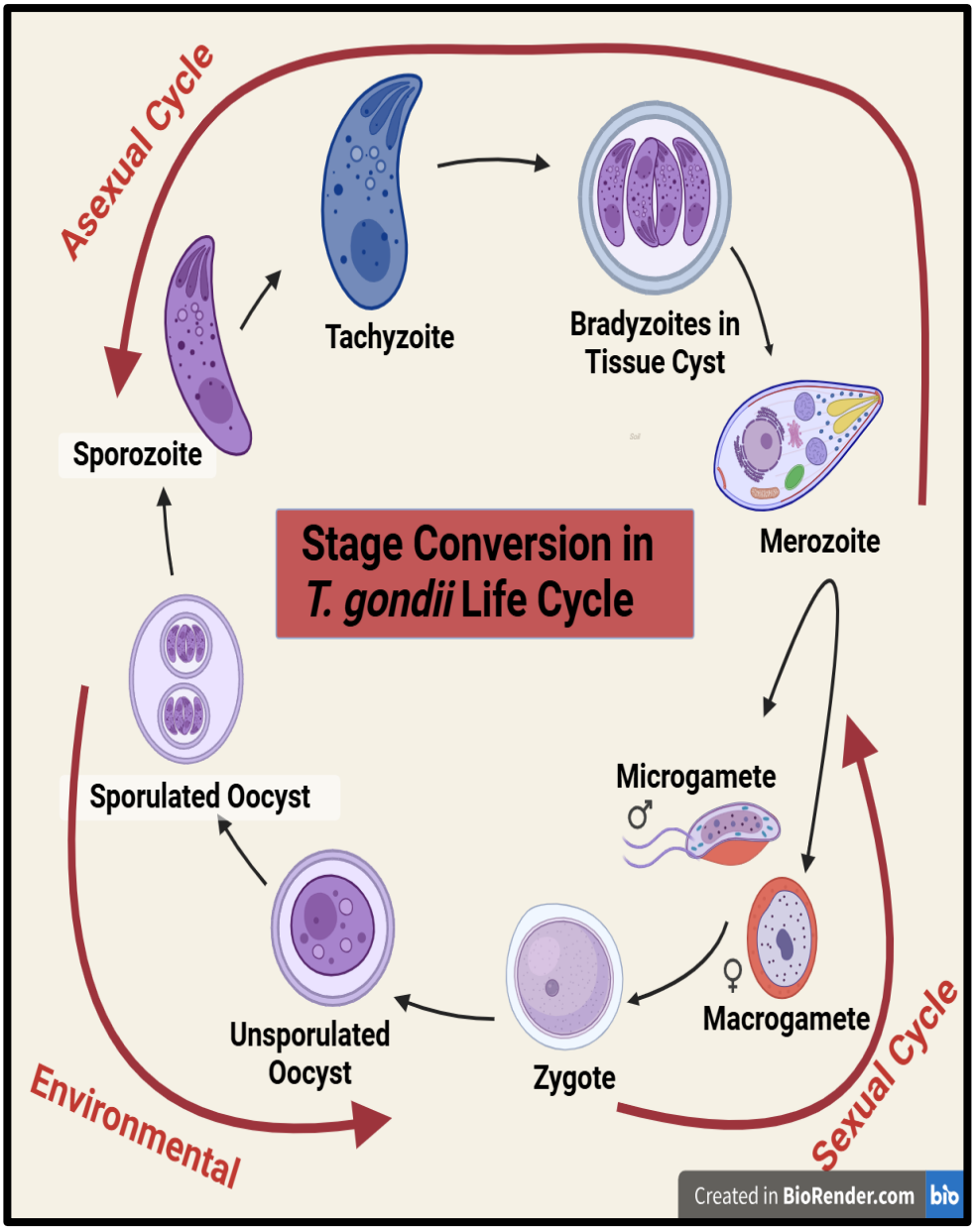

Fig. 2: Developmental differentiation in *T. gondii* life cycle

The seroprevalence rate reaches 51–72% among countries in Latin America including Argentina, Brazil, Cuba and Venezuela and 54–77% across the Gulf of Guinea West African countries like Benin, Cameroon and Congo (Gessain & Cassar, 2012). The seroprevalence rate among women of childbirth age in Southeast Asia together with China and Korea ranged between 4–39% (Hu et al., 2022). The Scandinavian countries together with other cold-climate areas demonstrate low seroprevalence rates with results ranging from 11 to 28%. Evidence suggests that standard *T. gondii* infections persist as a natural part of human populations worldwide (Figure 3) (Olsen et al., 2020).

Figure 3 indicates the ingestion of *T. gondii*. (A) The parasite spreads to humans through consuming raw meat containing encysted bradyzoites together with food intake of sporozoites inside oocysts. (B) Bradyzoites or sporozoites that enter the small intestine lumen proceed to penetrate intestinal enterocytes which line its walls. The parasites develop tachyzoite morphology (C) followed by fast multiplication (D) before leaving the cell (E). (F) The parasites penetrate lamina propria cells through successive tissue layers until reaching the immune cells which reside within this area. (G) When infected local immune cells produce chemokines they activate both moving capacities and defensive capabilities of passing immune cells (Pittman & Knoll, 2015).

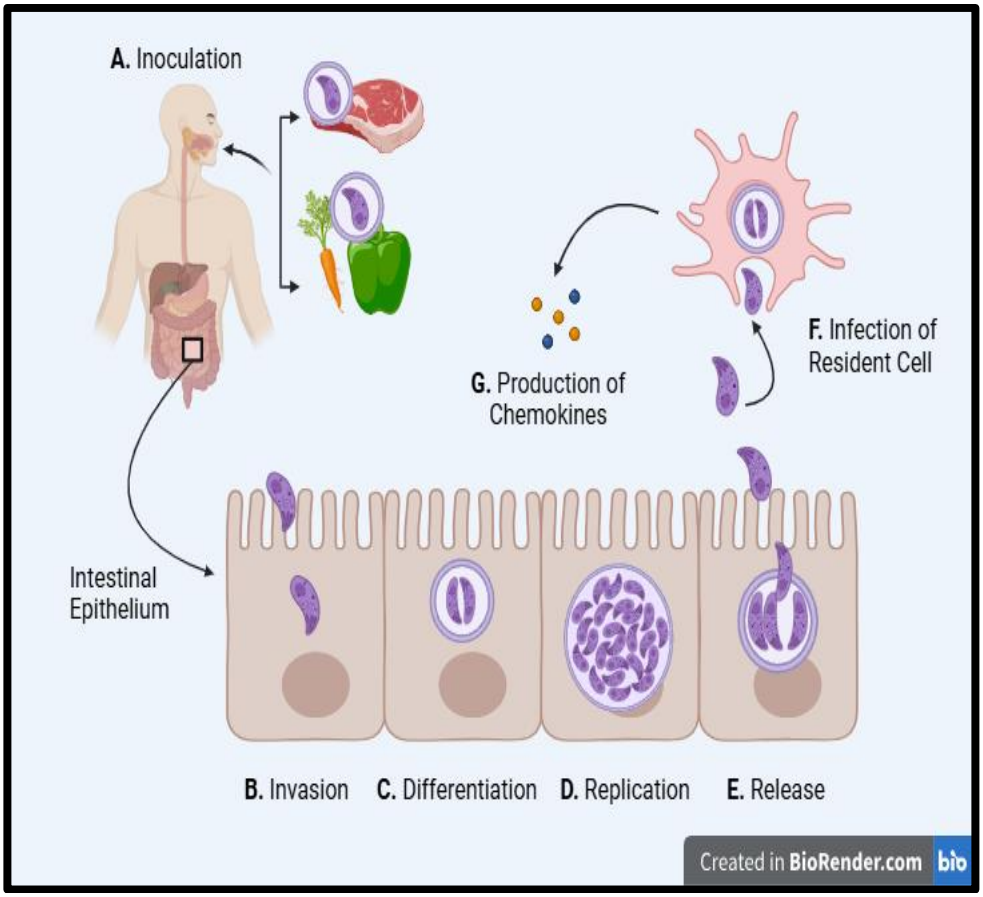

Fig. 3: Infection Dynamics of *T. gondii* After Ingestion

Current Treatments and Research Advances in Toxoplasmosis Management

The best treatment method for toxoplasmosis involves giving patients both pyrimethamine and sulfadiazine medications since the drugs work combined to inhibit folic acid synthesis. The treatment causes severe side effects including hypersensitivity reactions and bone marrow suppression as well as teratogenic effects to patients (Costa et al., 2021). Anti-inflammatory drug administration in combination with standard treatment helps to restrict further retinal damage throughout ocular toxoplasmosis cases (Morais et al., 2018).

The treatment of congenital toxoplasmosis involves using spiramycin alone or adding sulfadiazine and pyrimethamine depending on the pregnancy stage. The combination treatment produces toxic effects by suppressing bone marrow but the addition of folinic acid helps reduce these adverse effects (Dzitko et al., 2016).

The S48 strain-based live and attenuated tachyzoite vaccine known as Toxovax functions effectively to protect sheep but scientists have not discovered any therapeutic vaccine solution for toxoplasmosis in humans and other animals. Scientific investigations have studied vaccine type links to immune responses across various animal species where different antigens including attenuated and killed vaccines and DNA vaccines received analysis. Research work has employed multiple *T. gondii* antigens together with various adjuvant types (Liu et al., 2012). The research emphasizes that additional studies need to be conducted to develop proper toxoplasmosis treatments. Modern nanomedicine shows promise for fighting toxoplasmosis through its function as a medication transport agent. These carriers enable pharmacokinetic control, higher drug availability, precise release administration as well as decreased toxicity effects in their drug delivery role (Khalil et al., 2013).

General Aspects of Nanomaterials

Nanotechnology functions as the scientific discipline which focuses on controlling materials sized between tens and hundreds of nanometers. The small particle size enables these materials to establish distinct cellular interactions on the cell membrane surface as well as within cell compartments which results in the modification of their physicochemical behavior (Salata, 2004). Liposomes together with various nanomaterial types represent fundamental elements in nanomedicine practice as small spherical phospholipids or cholesterol vesicles. There are two fundamental nanoparticle categories which include nanocapsules and nanospheres. Nanomedicine applications use materials of three types: metals, lipids and polymers (Gutiérrez et al., 2016).

Metallic nanoparticles use well-defined small noble metal clusters to exist in their zerovalent state. The most widely produced silver nanoparticles give antimicrobial as well as anti-inflammatory properties and aid in medical imaging while enabling antibody conjugation but iron nanoparticles provide magnetic characteristics and show promise for tumour treatment (Edmundson et al., 2014). Nanoemulsions show differences from metallic nanoparticles. The heterogeneous composition of nanoemulsions forms two incompatible phases that include water-based oil in water (O/W) and oil-based water in oil (W/O) structures where oil or water determines the particle core composition. As a part of this discussion scholars need to recognize solid lipid nanoparticles containing lipids in solid form. Controlled drug or molecule release behaviour occurs through these two lipid nanomaterial types (Mukherjee et al., 2009).

Polymeric nanoparticles serve as solid systems having dual properties that are bio-compatible and biodegradable so therapeutic agents can dissolve inside them while absorption happens or they can maintain an encapsulated form within the polymeric matrix. Both synthetic poly (D, L-lactic-co-glycolic acid) (PLGA) and polyethylene glycol (PEG) and polyester biobeads exist alongside natural alginate insulin and chitosan in nanomaterials (Chan et al., 2010).

Nanomaterials function as two distinct mechanisms either through direct microbe interaction or delivery methods. Pharmacological agents or molecules can benefit from this role by allowing the targeting of specific pathogens especially those located inside cells leading to better drug stability and bioavailability management alongside controlled drug release capability and activity enhancement and degradation protection and safety improvements (Khalil et al., 2013; Gutiérrez et al., 2016). Multiple forms of nanomaterials presented in Figure 4 enable diagnosis and treatment methods and immunization development for preventing various infectious diseases including toxoplasmosis (Torres-Sangiao et al., 2016).

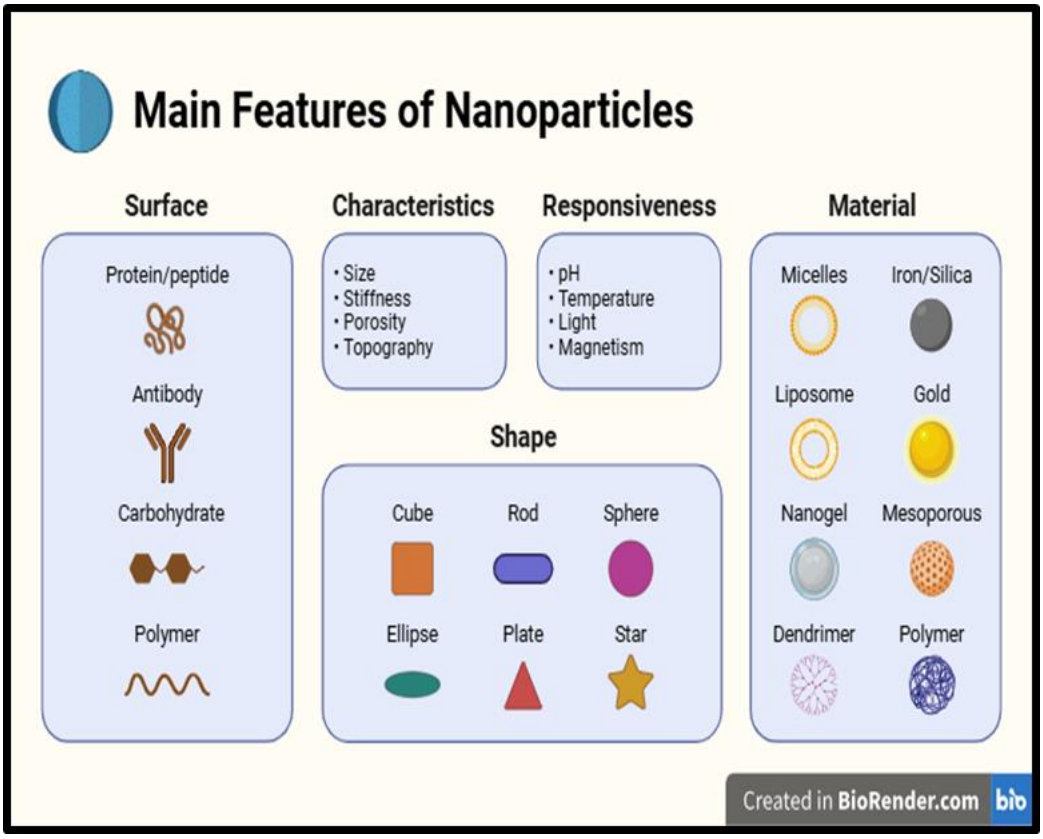

Fig. 4: Different Features of Nanoparticles

Nanomedicine in the Treatment of Toxoplasmosis

Nanotechnology applies useful drug delivery systems to enhance drug pharmacokinetic profiles. A higher area of solubility combined with increased stability, a faster dissolution rate and expanded surface area leads to enhanced drug bioavailability according to the principles of nanotechnology (Verma et al., 2003).

Research applying nanotechnology has demonstrated effective results for enhancing treatment against infections caused by *T. gondii*. Treatment involves the use of metallic silver, gold nanoparticles, various polymeric nanoparticles, lipid-based carriers, liposomal vehicles and nanosuspensions which incorporate drugs or molecules (Table 1).

(Gaafar et al., 2014) tested polymeric nanoparticles which included natural amino polysaccharide chitosan (CSNP) and silver nanoparticles (AgNP) both individually and as a combined (CSNP + AgNP) form using a murine toxoplasmosis model. Treatment of Swiss mice who received tachyzoites of *T. gondii* virulent strain RH with AgNP and CSNP + AgNP showed a decrease in parasite numbers within their liver and spleen tissues. This treatment method paralyzed motility while deforming peritoneal exudate tachyzoites through the formation of multiple grooves which resulted in irregular papules and large projections with disorganized conoid structures seen by scanning electron microscopy. The single administration of CSNP did not produce similar outcomes. The implementation of nanoparticles as a treatment produced increased IFN-γ levels throughout the infected groups while peak results manifested within treatment groups containing AgNP and CSNP + AgNP.

Similarly, (Anand et al., 2015) evaluated the impact of administering lactoferrin (BLF) which sequesters iron and fights multiple microorganisms through both oral and BLF-NC which loaded polymeric nanocapsules made from alginate-chitosan (two biodegradable polymers) to BALB/c mice suffering from *T. gondii* tachyzoite infection. The delivery method using BLF-NC enhanced the tissue concentration of BLF. The treatment diminished inflammation while simultaneously decreasing parasite count as well as boosting reactive oxygen species (ROS) and nitric oxide (NO) production within liver and spleen tissues with higher effects observed in the BLF-NC group. The nanocapsule treatment data revealed elevated Th1 cytokine levels in the blood of affected mice according to the authors. The combined production of Th1 cytokines and ROS alongside NO resulted in parasite death within the tissues and enabled animal survival until day 25 post-infection.

Table 1: Nanomaterials combining molecules or drugs for toxoplasmic treatment experiments

Sr. No.	Nanomaterials	Drugs/molecules	Reference
1	Silver nanoparticles	--------	(Gaafar et al., 2014)
2	Gold nanorods	Conjugated with anti-*T. gondii*	(Pissuwan et al., 2007)
3	Gold nanospheres	Conjugated with anti-*T. gondii*	(Pissuwan et al., 2009)
4	Polymeric nanoparticles of chitosan	-------	(Gaafar et al., 2014)
5	Polymeric nanocapsules of alginate-chitosan	Lactoferrin	(Anand et al., 2015)
6	Polylactide (PLA)polymeric nanocapsules	Atovaquone	(Dimier-Poisson et al., 2015)
7	Liposomes	Recombinant IFN-γ	(Miao et al., 2011)
8	Nanosuspensions	Atovaquone	(Dunay et al., 2004)
9	Core lipid nanocapsules	Pyrimethamine	(Pissinate et al., 2014)
10	Drug-dendrimer complex	Sulfadiazine	(Prieto et al., 2006)
11	2-Hydroxypropyl-β-cyclodextrin	Resveratrol	(Bottari et al., 2015)

Experimental photothermic therapies remain focused on gold nanoparticles since these nanomaterials show excellent biocompatibility. The ability of gold nanoparticles to serve as effective tools against infections caused by *T. gondii* results from their dual properties of laser light absorption and antibody conjugation (Jain et al., 2006). Research investigations have established that laser interactions with gold nanoparticles together with anti-*T. gondii* antibodies show successful treatment properties (Pissuwan et al., 2007; Pissuwan et al., 2009). Pissuawan and colleagues researched gold nanorods ~39.5 nm (Pissuwan et al., 2007) and gold nanospheres ~20 nm (Pissuwan et al., 2009) nanoparticles that were bound to antibodies targeted at the *T. gondii* surface antigen from the RH strain through experimental trials. These conjugates bound to tachyzoites and the binding improved parasite killing in an in vitro study whose effect increased with greater amounts of laser irradiation doses. The authors demonstrated that anti-*T. gondii* conjugated gold nanospheres used for pretreating tachyzoites diminished their infection potential in Chinese hamster ovarian epithelium cells (CHO-K1) (Pissuwan et al., 2009). Researchers have developed core-shell latex nanoparticles of size ~213.4 nm to inhibit *T. gondii* RH strain tachyzoites growth while reducing infected J774-a1 macrophage line numbers (Leyke et al., 2012).

Liposomes as Drug Carriers for Enhancing Anti-Toxoplasma Therapy

The wide-scale use of liposomes has persisted as carriers to transport hydrophilic and lipophilic drugs and molecules since their development as a technological advance (Johnston et al., 2007). Liposomes function through direct or indirect effects on microorganisms which activate immune system response. (Miao et al., 2011) showed that activation of macrophages by recombinant IFN-γ (rIFN-γ) contained within liposomes led to a tenfold improvement in both hydrogen peroxide (H_2O_2) production and anti-Toxoplasma activity of free rIFN-γ and resulted in extended effects. (Tanaka et al., 2014) demonstrated the protective properties of *T. gondii* infections which involved stearylamine (SA) and phosphatidylcholine (PC) liposome formulations known as SA/PC-liposomes. The administration of SA/PC-liposomes to RH tachyzoites brought about substantial morphological alterations to the cells while simultaneously reducing their in-vitro presence to less than 5%. Before or after *T. gondii* infection of ICR mice resulted in an 80% increase in survival rate when mice received pre-treatment and a 70% increase in survival rate when mice received post-treatment with SA/PC-liposomes for 30 days.

The laboratory observations demonstrate that triclosan (TS) and other substances exhibit inhibitory effects on apicomplexan protozoan survival or growth (McLeod et al., 2001) yet their therapeutic applications remain restricted due to their low solubility. The biological capacity of TS gets elevated through liposomal encapsulation (Vandhana et al., 2010). The efficacy of TS and TS-liposomal as *T. gondii* cyst inhibitors was confirmed through experiments performed using Swiss mice infected with ME49 cysts (El-Zawawy et al., 2015) which led to a 20% and 70% reduction in infectivity. Visual examination of *T. gondii* cysts under scanning electron microscopy displayed both compressions and ledges within treated groups. The wall of bradyzoites in treated groups presented with partial deterioration when examined under transmission electron microscopy while showing extensive vacuolization and damaged membranes. The combination of TS-liposomes showed better performance than Tannic acid (TS) in lowering alanine aminotransferase (ALT) and aspartate aminotransferase (AST) levels.

Improving Bioavailability of Anti-*Toxoplasma* Agents through Nanotechnology

A natural compound named usnic acid exists in specific lichen species of the genus Usnea (Pramyothin et al., 2004). This substance displays multiple biological impacts which also act against protozoa. Transport to target cells can be improved by using liposomes because they address the toxicity issue and water insolubility challenge. (Si et al., 2016) conducted therapeutic effects analysis on usnic acid and usnic acid-liposome (~130 nm) through research with Swiss mice that received tachyzoites from the *T. gondii* RH strain through intraperitoneal injection. Research findings showed that mice administered liposomal usnic acid demonstrated better survival outcomes than mice receiving usnic acid alone. Atovaquone functions as a therapeutic drug for treating toxoplasmosis while showing preliminary signs of effectiveness against *T. gondii*

infections. The low solubility rate reported for atovaquone leads to reduced bioavailability levels in the body. Several investigations have studied how atovaquone bioavailability changes as a result of nanotechnology-based drug conjugation alongside its anti-*toxoplasma gondii* capabilities (Dunay et al., 2004).

Laboratory researchers investigated the efficacy of Atovaquone nanosuspensions by studying their ability to activate latent *T. gondii* infection through tests on murine interferon regulatory factor 8 knockout mice. *T. gondii* infection results in toxoplasmic encephalitis development (Dunay et al., 2004). The combination therapy using ASN 10 mg/kg intravenously elevated drug levels in mouse blood which led to complete protection against acute reactivated infections when follow-up atovaquone oral administration continued for seven days through which they prevented toxoplasmic encephalitis development without detectable brain or liver parasite or inflammatory activity. Apolipoprotein E integration with ASN failed to enhance brain barrier penetration when tested in the blood-brain barrier model or during treatment uptake in live animals while producing elevated ASN concentrations in brain endothelial cells (Shubar et al., 2011).

The survival rates of CF1 mice suffering from intraperitoneal *T. gondii* tachyzoites of the RH strain improved through treatment with pyrimethamine-embedded core lipid nanocapsules (PYR-LNC) according to (Pissinate et al., 2014). The research investigated the body distribution of conjugate complexes. The drug-dendrimer complex (ramified nanostructures) received analysis from (Prieto et al., 2006) for its resistance and stability along with anti-Toxoplasma activity tests in vitro. The research showed that sulfadiazine alone discharged all its content within 90 minutes yet the drug was preserved at 98% when encapsulated by SDZ-DG4.5 (anionic dendrimer) complexes which sustained release for up to 24 hours. SDZ-DG4 (cationic dendrimer) complexes maintained about 85% drug concentration under similar conditions. The cell infection rate was reduced by 60% after Vero cells were exposed to 0.03 μM SDZ-DG4 but 0.03 μM SDZ-DG4.5 achieved only 25% infection reduction. The research showed that sulfadiazine alone discharged all its content within 90 minutes yet the drug was preserved at 98% when encapsulated by SDZ-DG4.5 (anionic dendrimer) complexes which sustained release for up to 24 hours. SDZ-DG4 (cationic dendrimer) complexes maintained about 85% drug concentration under similar conditions. The cell infection rate was reduced by 60% after Vero cells were exposed to 0.03 μM SDZ-DG4 but 0.03 μM SDZ-DG4.5 achieved only 25% infection reduction. The drug release speed becomes slower when utilizing these complexes thus lengthening their repeating presence throughout biological systems.

Much research focuses on the medical applications of Resveratrol across different conditions while scientists also use nanomaterials to study its potential in toxoplasmosis management (Miller et al., 2009). Ample research material shows that resveratrol produces meaningful anti-inflammatory and antioxidative effects. Resveratrol becomes unstable upon exposure to digestive enzymes within the human gut and stomach acids passively degrade this substance in the body (De La Lastra & Villegas, 2007). Nanomaterials assist in enhancing drug bioavailability and activity for both resveratrol and other compounds by sustaining their stability against degradation. Bioavailability studies have evaluated the therapeutic effects of free resveratrol against resveratrol encapsulated with 2-hydroxypropyl-β-cyclodextrin (HPβCD) both in its pure form and in combination with sulfamethoxazole-trimethoprim (ST) through experiments using mice infected with toxoplasmosis. Swiss mice treated with free resveratrol-HPβCD or ST in combination with tachyzoites of the VEG strain (type III) developed decreased brain cyst counts and hepatic inflammation reported by the authors due to a synergy between the drugs. The combination of free resveratrol-HPβCD or resveratrol-HPβCD and ST administered to Swiss mice resulted in enhanced acetylcholinesterase (AChE) function which influenced acetylcholine degeneration compared to standard controls though it remained below levels of untreated infected animals. This research showed that resveratrol treatment did not change the functioning of creatine kinase yet demonstrated protective effects against brain inflammatory processes as a whole (Bottari et al., 2015). By applying free resveratrol and resveratrol-HPβCD to BALB/c mice who received *T. gondii* bradyzoites witnessed a decrease in brain cysts together with a decline in liver inflammatory infiltration. The free resveratrol together with the resveratrol-HPβCD complex failed to affect production levels of most proinflammatory cytokines. Combining TS with free resveratrol or resveratrol-HPβCD resulted in elevated IL-10 secretion compared to infected untreated animals.

Research by (Bottari et al., 2016) demonstrated that combining free resveratrol with resveratrol-HPβCD grants synergistic advantages for treating *T. gondii* bradyzoite-infected Swiss mice with ST. This composing therapy reduced brain cyst counts while decreasing hepatic inflammatory cell number together with increasing oxidative protein levels and brain total oxidation status despite liver stability. The analysis showed that brain plasma total antioxidant capacity (TAC) alongside the ferric reducing ability of plasma increased when resveratrol and ST were combined. Hepatic antioxidants showed the most significant growth after resveratrol-HPβCD treatment in combination with ST along with exhibiting maximum benefits on mnemonic performances. This mnemonic effect emerges because the brain receives the resveratrol slowly during the proposed mechanism while the free form dissipates quickly through metabolism. Different types of nanomaterials improve both drug availability and timed-release properties and protect compounds from breakdown to enhance their therapeutic impact while reducing their toxic nature.

Conclusion

As a highly adaptable protozoan parasite, *Toxoplasma gondii* spreads across diverse warm-blooded hosts by infecting felines which act as its definitive host. Transmission happens when people swallow either tissue cysts or oocysts which are the parasite's life cycle stages. This cycle includes both sexual reproduction and asexual reproduction changes. The majority of infections produce no symptoms yet severe toxoplasmosis develops only in immunocompromised patients or when infection occurs during pregnancy. The standard toxoplasmosis treatment method consists of sulfadiazine and pyrimethamine therapy which doctors support with folinic acid to prevent bone marrow toxicity. The current therapeutic options for toxoplasmosis suffer from two major disadvantages: toxicity effects and limited drug absorption in the body. Modern nanotechnology research demonstrates significant potential to boost drug therapy against *T. gondii* infections. Scientists have studied different kinds of nanoparticles from silver to gold together with polymeric and lipid-based carriers because they demonstrate improved delivery of drugs along with better bioavailability and therapeutic action. Research shows anti-*T. gondii* antibody-conjugated gold nanoparticles provide photothermal therapy as an effective method to decrease parasite survival under laser treatment illumination. Liposomal drug delivery systems improve stability alongside the effectiveness of anti-Toxoplasma agents such as atovaquone, resveratrol and triclosan. Drug release control

from polymeric nanocapsules and dendrimers helps parasite clearance and decreases drug toxicity. Lactoferrin nanocapsules along with usnic acid-loaded liposomes show strong antitoxoplasmic properties by strengthening immune response while preventing parasite multiplication. More research needs to be conducted to enhance nanoparticle formulations, examine enduring safety aspects and launch clinical uses of these therapies. The use of nanotechnology in toxoplasmosis therapy creates substantial opportunities to enhance medical results, particularly among vulnerable patient groups. Future research should concentrate on creating nanotherapeutics that are effective but safe and affordable for improving contemporary treatment methods to diminish toxoplasmosis worldwide burden.

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